Experimental Study of the Hydraulic Behaviour

of

Melbourne Silt

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DECLARATION

This is to certify that except where due acknowledgement has been made, the work is that of the candidate alone, that the work has not been submitted previously, in whole or in part, to qualify for any other academic award, that the content of the thesis is the result of the work which has been carried out since the official commencement date of the approved research program, and that any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Candidate

Lijing Wang

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To the memory of my beloved grandfather, forever loved, missed and remembered.

NOTATION

σ' effective stress

μ_a pore air pressure

μ_w pore water pressure

χ parameter related to the degree of saturation in effective stress equation

$\overline{\sigma}$ net stress

s matric suction

δ_{ij} Kronecker’s delta

$\delta_{ij}^{'}$ average stress

S_e^{ref} the effective degree of saturation

S_r^{ref} residual degree of saturation

θ_r residual water content

θ_s saturated water content

S_{ae} suction in air entry value

S_{re} the residual suction

μ_d fitting parameter in Brooks and Corey SWCC equation

α_d fitting parameters in Fredlund and Xing SWCC equation

β_d fitting parameters in Fredlund and Xing SWCC equation

γ_d fitting parameters in Fredlund and Xing SWCC equation

$a_{d/w}$ fitting parameters in Van Genuchten equation

$m_{d/w}$ fitting parameters in Van Genuchten equation

$n_{d/w}$ fitting parameters in Van Genuchten equation

D minimum horizontal distance

I_{ps} shrinkage index

θ volumetric water content

ψ total suction

ψ_s osmotic suction

S_r degree of situation

S_e effective degree of saturation

ε_v volumetric strain

ε_v^e volumetric strain in elastic region

ε_v^p volumetric strain in plastic region

κ logarithmic elastic modulus

λ logarithmic hardening constant

e void ratio

e_0 initial void ratio

m_0 initial mass of soil sample in SWCC test

V_0 initial volume of soil sample in SWCC test

w_i initial water content in SWCC test

m_w^0 initial water mass in SWCC test

V_w^0 initial water volume in SWCC test

m_s the mass of soil particles in SWCC test

V_s the volume of soil particles in SWCC test

V_w^1 new water volume in SWCC test

h soil sample ring height

D_{ring} soil sample ring diameter

ABSTRACT

Soil, partially saturated in water, is referred to as unsaturated soil. Unsaturated soil has a very complicated behaviour. A change in the degree of saturation may cause significant changes in soil volume, shear strength and hydraulic properties. There has been growing interest in the thermo-hydro-mechanical behaviour of unsaturated soils due to the increasing number of geotechnical problems involving thermal and unsaturated issues. For example, soils surrounding the buried nuclear waste would certainly experience elevated temperature and partially saturated conditions. The soil-water characteristic curve (SWCC) or soil-water retention curve (SWRC) has emerged as a widely used estimation tool for obtaining hydraulic properties of a soil in unsaturated state. However, currently available test results and theoretical investigation on SWCCs are mainly limited within isothermal states, and deformation caused by temperature variation is usually neglected for simplification purpose.

In this study, a series of experiments have been carried out to investigate the effect of thermal and initial void ratio on soil-water characteristic curves (SWCCs) of unsaturated soils. The soil samples were collected from a field site at Glenroy – a northern suburb of Melbourne. The samples used in the experiments were remoulded, to eliminate possible effects due to natural differences between the composition and structure of undisturbed soils samples, as well as anisotropy and non-homogeneity within individual samples. The samples were firstly dried in an oven at a temperature of 105°C. They were then sieved, and placed into a special-purpose pre-consolidation cell. A Fredlund SWCC device with a temperature controlled cell has been be employed to conduct temperate-controlled SWCC tests.

The experimental work in this research consists of three stages, and each stage includes three tests. The first stage focuses on the conventional SWCC test. The purposes of conducting this stage is to prepare testing of soil samples and to set up Fredlund SWCC devices. Ensuring devices are in good working order, and the air entry value of the soil sample is in a good

range, whilst estimating the duration of each test. Also, study the behaviour of the testing soil and set a benchmark for stage two and three experimental work.

The second stage consists of SWCC testing of soil samples with different initial density. The obtained SWCCs were plotted together with SWCCs from Stage one to compare. The results clearly shows that the air entry value is completely different when the initial density of soil is different. The initial density has an important effect on the SWCC when the matric suction has exceeded air entry value. When the void ratio increases, the soil water retention ability decreases. In other words, there is an incremental relationship between the degree of saturation and the initial density. The soil sample with a large void ratio has a relatively large volume change compared to the sample with a low void ratio.

The third stage is the non-isothermal SWCC test. The results indicates that there is a strong relationship between temperature, suction and soil hydraulic properties. The thermal effect on liquid-gas interfacial tension and the thermal deformation both impact the soil water retention behaviour. The increase of the temperature can decrease the soil water retention behaviour of the testing soil. The increase of the temperature can also increase the volume change of the testing soil. There is a significant influence of temperature on the air entry value of the testing soil.

As above, the outcomes of the study lead to a better understanding and interpretation of the thermal effect and the initial density effect on SWCCs for unsaturated soils. Therefore, when it comes to the design for unsaturated soil in practice, the behaviour of unsaturated soil can be considered to reduce the risk of damages on foundation as well as the cost of construction

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 INTRODUCTION

1.1 Background

Soil is one of the most common types of material on the earth. When soil fully saturated with water, is often referred to saturated soil. Generally, unsaturated soil is composed of soil particles, water and air. However, it may be necessary to include the fourth phase which called air water interface. Under such condition, the degree of saturation is less than 100%. Practically unsaturated soil can be fully saturated (degree of saturation reaches 100%) under natural condition such as rainfall or under laboratory condition such as reconstitution process.

Unsaturated soil is involving in everyday engineering practices around the world, for example, most geo- structure, such as foundations, roads or even nuclear waste disposal sites. Damage to infrastructures founded on unsaturated expansive soils has been widely reported in many countries such as China, India, Israel, South Africa, Spain, Sudan, the United Kingdom and the United States of America (Li and Cameron, 2002; Li et al. 2014). The problems are particularly significant in Australia as approximately 20% of the total land area is covered by unsaturated expansive soils, and these areas are often associated with a harsh semi-arid climate (i.e. long dry period followed by a short period of relatively high rainfall). The presence of the upper soil layers is usually unsaturated due to this climate.. Therefore, geotchnical problems of significance to Australia are those associated with unsaturated soils (Li and Zhou 2013).

In 1936, unsaturated soil has attracted researcher’s interest for the very first time, as the first study has been presented in the First International Conference on Soil Mechanics and Foundation Engineering (ISSMFE) Harvard. However, after that, the study of unsaturated soil behaviour had stagnated due to various reasons and until today, the study is still very much limited. In terms of the development of soil mechanics, there are many advanced theories and practical progresses been developed in the early years, however, most of them are for saturated soils.

Behaviour of unsaturated soils is much more complex than that of saturated soils. When the degree of saturation varies but stress level constant, soil can result in a tremendous volume change, appear in the form of expanding or swelling. If stress levels varies at the same time, the behaviour of unsaturated soil could be more complicated. This is a threat to the foundation of the infrastructure. Therefore, as pointed by Fredlund and Rahardjo (1993), soils which are unsaturated, form the largest category of materials, which do not adhere in behaviour to classical, saturated soil mechanics. In a simple terms, designation of geo-mechanics principles, experiments which are saturated soil based should not be applied to unsaturated soil.

As pointed by Fredlund (2006), the development and implementation of unsaturated soil mechanics has been slow down by a number of challenges. Those challenges can be roughly divided into two aspects: theoretical and experimental, and they are complementary to each other. Theoretically, argument on the selection of constitutive variables to analysis the mechanical and hydraulic properties of unsaturated soils has never stopped (Zhou 2011). Experimentally, it is difficult to control the accuracy of the test result as the duration of the experiment is usually long, how to maintain the saturation of high air- entry value ceramic is problematic, therefore air-diffusion would occur, influence the accuracy of the test result. The aforesaid is hard to be avoided. Hence, there are very few reliable testing results on unsaturated soil available.

The soil- water characteristic curve (SWCC) is a fundamental soil water relationship for unsaturated soil. It has been used to define the hydraulic properties of soil. SWCC has also been used for estimating unsaturated soil properties such as shear strength, stress- strain relationship (Fedlund, Sheng et al. 2011). The SWCC can also be called soil- water retention curve (SWRC), it can be defined as the relationship between the volumetric water content (θ) or degree of saturation (S_r) and the matric suction (s) or soil water potential (ψ) (Li et al. 2007). It is usually obtained by drying or wetting a soil sample under a constant stress while monitoring the drainage volume and total volume change of the soil (Zhou, Sheng et al. 2011). Many researchers agree that SWCC is one of the indispensable components in unsaturated soil mechanics. Gens(2010) pointed that SWCC is an obligatory element in Bishop's effective stress; In the application of unsaturated soil modelling, is the first constitutive variable. Zhou (2011) indicated that degree of saturation is more suitable for the supplementary constitutive variable compared with suction , which proved the vital importance of SWCC in hydro- mechanical coupled constitutive modelling of unsaturated soil.

It has been proved that there are numbers of factors that could influence SWCC. They can be roughly divided into two groups: internal and external. The internal factors, relating to soil itself, for example particle size distribution, pore size and pore shape distribution and specific surface area. The external factors that are depending on external conditions such as environmental condition. Stress and temperature are two of the typical factors. In current practice, under laboratory condition, internal factors effects can be monitored and analysed by using current SWCC equations, however, how to take external factors into account is problematic. For example, due to different external stress state and stress history, the density of the soil would be varies; however, researchers cannot simply analysis those soils as different types. Therefore, SWCC results with a consideration of effects by external factors is very much limited.

Recently, many researchers proposed a number of models on the effects of soil density on SWCC. For example, Sheng and Zhou (2011) proposed a new incremental relationship between degree of saturation and void ratio, constant stress is proposed to replace constant volume in the proposed model for SWCC result. Zhou et al (2011) further modified the incremental relationship to model the effect of initial density on the soil water retention behaviour.

At the same time, research also shows the study of thermal effects on SWCCs is still limited. The earliest record about thermal effect on soil was in 1937, when Richards and Neal (need reference here) pointed out that capillary pressure decreases when soil has warmed during morning period. However, this finding did not draw much attention until last century, when the global environment has gradually deteriorated and lead to a series impacts. For example, global warming has caused the temperature raise, decline in soil water retention, unsaturated soils become widespread. Also, with the growing development of the European nuclear industry, disposal of nuclear waste will lead to a long term impact to the surrounding environment in which heat energy release, rise up the temperature and result in unsaturated soil. Thus, the thermal effects on unsaturated soil can no longer be neglected in order to prevent damage of geotechnical structure caused by unsaturated soil.

In the past decade, a number of researches proposed several models to interpret the constitutive behaviour of unsaturated soil under different temperatures, e.g., Constantz 1981, Romero, Gens et al. 1999, Masin and Khalili 2011, Zhou, Sheng et al. 2011). . The non-isothermal van Genuchten's model is the one which has been widely applied to describe the dependency of SWCCs on the temperature but the deformation due to the temperature variation has been ignored in this model (Zhou, Sheng et al. 2011). Therefore, many researchers realised the importance of including the deformation of thermal effect on SWCC and proposed many theoretical approached papers on this effect. Very recently, Zhou proposed a new novel approach which includes the effect on liquid- gas interfacial tension and the thermal deformation, both effect on SWCC (Zhou, Sheng et al. 2011) .

1.2 Research Aims

The objective of this study is to investigate on the hydraulic behaviour of unsaturated soil via SWCC. Testing material is the selected Melbourne silt and has been reconstituted under laboratory condition. A suction and temperature controlled oedometer was used to conduct temperate-controlled SWCC tests. The aim of this study is to get a better understanding of how the soil related factor (e.g. initial density) and the environment related factor (e.g. temperature) affecting the hydraulic behaviour of Melbourne silt. The experimental results will be presented and discussed. Also, the following questions will be answered:

- What is the current progress on the hydraulic behaviour of deformable unsaturated soil?
- How does the different initial density affecting on soil's water retention behaviours in the laboratory?
- How does the temperature variation affect soil's water retention behaviours in the laboratory?
- How to interpret those effects on water retention behaviour especially when soil is considered as a deformable material during drying/ wetting?

1.3 Thesis Arrangement

This thesis is divided into four chapters, with Chapter 1 being this introduction.

Chapter 2 provides a detailed literature review including unsaturated soil problems, description of the soil water characteristic curve and current progress/ understanding of unsaturated soil hydraulic behaviour via SWCC.

Chapter 3 gives a detailed description of the laboratory experiments. The methodologies and results of the experiments are also described, discussed and compared.

Chapter 4 is presenting the final conclusions and recommendations for future research.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

Soil partially saturated with water is referred to as unsaturated soil. Unsaturated soil has very complicated behaviour. The fundamental frameworks of soil mechanics in the past decades have been mainly focused on the saturated soil. Recently, there has been an increase of interest in unsaturated soil as a result of damages to infrastructures caused by movement of unsaturated soil.. Many researchers are trying to extend the theories of unsaturated soil mechanics however the current progress is still slow. In this chapter, special attention is paid to the current development of soil water characteristic curve of unsaturated soils.

2.2 Soil-water characteristic curve

The soil-water characteristic curve (SWCC) is commonly used to present the behaviour of deformable unsaturated soil. SWCC is also known as the soil-water retention curve (SWRC). It gives the relationship between the amount of water in the soil (i.e. the degrees of saturation) and the soil suction. Many properties of unsaturated soil can be obtained from the SWCC such as shear strength, coefficient of permeability and the amount of water contained in the pores at any suction(Mualem 1976, Fredlund, Xing et al. 1994, Fredlund, Xing et al. 1996, Wheeler 1996, Assouline 2001). In other words, SWCC presents the basic characteristics of unsaturated soil.

Figure 2.2-1 is an example of a soil-water characteristic curve. The air entry value (AEV) is when air start to enter the largest pores of the soil. Fredlund (1996) stated that AEV can be understand as the suction required to cause desaturation of the largest pores. It can be obtained from SWCC curve as shown in Figure 2.2-1 . It is important to understand that the desaturation will only occur when the suction is greater than the air entry value.

SWCC usually consist of three stages during drying and wetting process:

- Saturation zone: Also can be called capillary saturation zone. In this zone, the pore water is in tension and the soil is considering as essentially saturated due to capillary force. This zone continues until the air start to enter the large pore in the soil sample.
- Desaturation zone: When soil suction value is exceeded the air entry value, the pore water in the soil starts to be replaced by air and as a result, a significant decrease in the degree of saturation. This zone ends when an increase in soil suction does not result in significant changes in the degree of saturation.

- Residual stage: The zone of residual saturation is terminated at oven dry conditions where water content equals zero, corresponding to a soil suction of approximately 10^6 kPa(Croney and Coleman 1961).

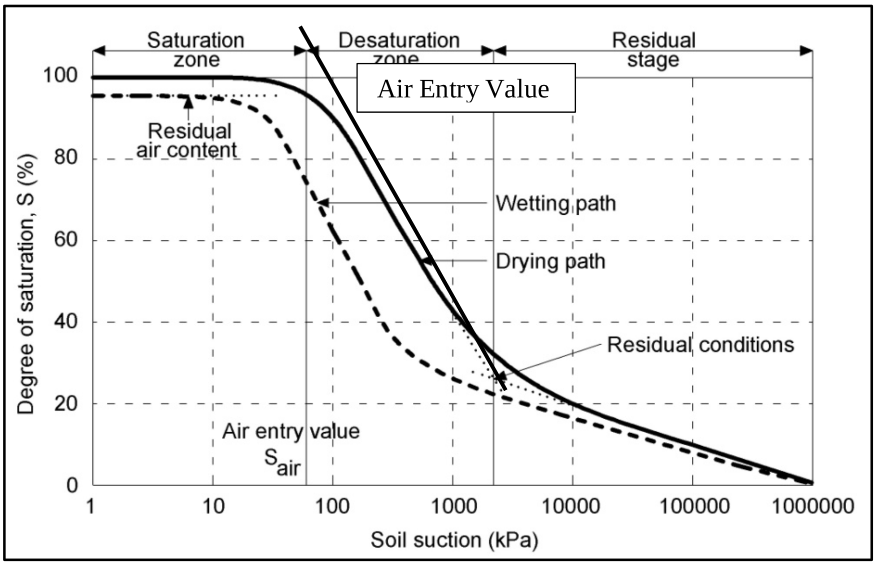


Figure 2.7.1-1Example of soil-water characteristic curve (Sillers et al. 2001)

The first SWCC equation was proposed in 1907 by Buckingham (Brady 1999), not long after that, many researchers have been proposed different equations for SWCC simulation. For example Gardner (1956), Brooks and Corey (1964), Mualem (1976), van Genuchten (1980), Fredlund and Xing (1994) and Li (2005). There are many factors which could influence SWCC. They can be roughly divided into two groups: internal factors and external factors. Internal factors are dependent on the soil type, which includes distribution of pore size, pore shape, particle size, specific surface area and chemo-physical properties of soil phases. The external factors are related to external or environmental conditions surrounding the soil and can usually change continuously over a range of values. Typical examples of external factors are stress and temperature. As stated by Zhou et al. (2011), it is difficult to treat samples from a soil with different densities as an entirely different soil for the purpose of modelling. This can also apply to a soil sample under different temperatures. The SWCC only presenting the characteristic of a soil at the specific density and under a particular temperature.

2.3 Empirical SWCC Equation Development

From the beginning of the 20th century, numerous empirical equations have been proposed to simulate SWCCs for various soils (Gardner 1956, Brooks and Corey 1964, Mualem 1976, van Genuchten 1980, Fredlund and Xing 1994). Most of them are three parameter equations. The model parameters *a, n* and *m* are set as variables to define the model. The parameter *a* is a suction related value. The parameter *n* is related to the rate of change of the desaturation zone of the soil –water characteristic curve. The parameter *m* is related to the asymmetry of the curve about the inflection point (W. Scoot Sillers, Fredlund et al. 2001).

Gardner Model(1956)

In 1956, Gardner proposed an equation used to model the permeability coefficient of unsaturated soil. It is also has been adopted to model the soil-water characteristic curve.

$$\mathbf{S}_{\boldsymbol{r}} = \frac{\mathbf{1}}{\mathbf{1+a}\boldsymbol{\psi}^{\boldsymbol{n}}} \qquad 2.3\text{-}1$$

Where, S_r is the degree of saturation, ψ is the soil suction and this equation uses two fitting parameters *a* and *n*.

Brooks and Corey Model (1964)

The Brooks and Corey equation is one of the first models proposed for the soil-water characteristic curve. The degree of saturation of the soil is assumed to be constant when suction value is less than the air entry value. When soil suction exceeds the air entry value, the degree of saturation is assumed to be an exponentially decreasing function of soil suction. The equation can be written as follows, which uses two fitting parameters, namely. a and n.

$$\begin{cases} \boldsymbol{S_r = 1} & \boldsymbol{\psi < a} \\ \boldsymbol{S_r = (\frac{\psi}{a})^{-n}} & \boldsymbol{\psi > a} \end{cases} \qquad 2.3\text{-}2$$

Mualem Model (1976)

The Mualem model is commonly referred in the geotechnical literature.

$$\boldsymbol{S_r = \frac{1}{(1+(a\psi)^n)^{(1-1/n)}}} \qquad 2.3\text{-}3$$

This model is very similar to the Burdine (1953). It provides an acceptable fit of data from various soils. Also, W. Scott pointed that in this model, the effect of one parameter can be distinguished from the effect of the other parameter. However, this is a model with two parameters, 1- 1/n is restricts its flexibility (shape of the SWCC).

Van Genuchten Model(1980)

The Van Genuchten model is one of the most popular models. It has been widely used due to its flexibility and simplicity. This model also has been further modified by many researchers.

$$\boldsymbol{S_r = \frac{1}{(1+(a\psi)^n)^m}} \qquad 2.3\text{-}4$$

The advantages of this original Van Genuchten model are as follow: this model is more flexible because it consists of three parameters rather than two, and it is a continues model where Brooks and Corey (1961) does not have a continuous function for the entire SWCC.

Fredlund and Xing Model (1994)

In 1994, Fredlund and Xing proposed a three parameter continues model for SWCC:

$$\mathbf{S_r} = \frac{\mathbf{1}}{(\mathbf{ln}\left(\boldsymbol{e}+\left(\frac{\boldsymbol{\psi}}{\boldsymbol{a}}\right)^{\boldsymbol{n}}\right))^{\boldsymbol{m}}} \qquad 2.3\text{-}5$$

This model has great flexibility to fit a wide range of data. Each parameter in the equation is meaningful. As pointed out by W. Scoot Sillers (2001), the effect of one parameter in the equation can be distinguished from the effect of the other two parameters.

2.4 Effect of Initial Density on SWCC Equations

As mentioned before, SWCC are affected by many factors, one of the specific factor is the density of soil. The density of the soil depends on the stress and suction state, also controlled by the pervious stress and suction history. As pointed by Zhou et al., (2011) that density variation of a soil cause significant variation of the SWCC and this variation is a common feature of natural soils. In 1954, Croney and Coleman first raised the relationship between soil structure and suction, after that, for some reason, the study progress on effect of soil initial density on soil hydraulic properties didn’t improve much until 1966, when Labliberte et al published a paper on properties of unsaturated porous media. In the past decade, the study on how the initial density of soil effect on SWCC has gained many researchers’ attention, such as, Ng and Pang, (2000); Gallipoli et al., (2003); Wheeler et al., (2003); Sun et al., (2008); Khalil et al., (2008); Miller et al., (2008); Nuth and Laloui, (2008); Masin, (2010); Sheng and Zhou, (2011).

Gallipoli proposed a relationship between degree of saturation, suction and specific volume for deformable soils as shown below:

$$\boldsymbol{S_r} = \left\{\frac{\mathbf{1}}{\mathbf{1}+[\emptyset(\boldsymbol{v}-\mathbf{1})^{\boldsymbol{\varphi}}\boldsymbol{s}]^{\boldsymbol{n}}}\right\}^{\boldsymbol{m}} \qquad \textbf{(2.4-1)}$$

where m,n,φ and ψ are soil constants.

This equation is based on the SWCC equation which proposed by van Genuchten (1980), but with additional consideration of specific volume:

$$\mathbf{a} = \emptyset(\mathbf{v}-\mathbf{1})^{\boldsymbol{\varphi}} \qquad \textbf{(2.4-2)}$$

where ∅ and φ are soil constants.

As pointed out by Zhou et al (2011) that Tarantion (2009) proposed a SWCC equation which is very similar to the one by Gallipoli. The model is based on the empirical power function of the water ratio e_w.

Sun et al (2008) proposed a hydraulic model for unsaturated soil, as shown below. This proposed model considering the change in soil volume and change in matric suction can be resulted in the change of the degree of saturation.

$$\mathrm{d}\boldsymbol{S_r} = \boldsymbol{\lambda_{s_r}}\frac{\boldsymbol{ds}}{\boldsymbol{s}} + \boldsymbol{\lambda s_e de} \qquad \textbf{(2.4-3)}$$

Where s is suction, S_r is the degree of saturation, λ_{se} is the slop of the S_r-e curve under constant suction, e is the void ratio and λ_{sr} for main wetting or drying curve.

Masin (2010) proposed s model to predict the dependency of a degree of saturation on void ratio and suction by using the effective stress principle for unsaturated soils.

$$\dot{S}_r = \frac{\partial S_r}{\partial s}\dot{s} + \frac{\psi - S_r}{e}\dot{e} \qquad \textbf{(2.4-4)}$$

As stated by Masin (2010), the first part of the equation is under constant void ratio, to quantifier the dependency of S_r on suction and the second part of the equation is under constant suction, to evaluates the dependency of S_r on void ratio.

Sheng and Zhou (2011) proposed a coupling hydraulic with mechanical model to present an incremental relationship between degree of saturation and initial void ratio to describe the effect of initial density on SWCC.

$$\mathrm{d}S_r = -\frac{S_e}{e_1}(1 - S_e)^{\xi} de \qquad \textbf{(2.4-5)}$$

where S_e is the effective degree of saturation, e_i is the initial void ratio at the start of the SWCC test and ξ is the fitting parameter.

The above mentioned models are simulating the effect of the initial density on the degree of saturation as a result present in SWCC under inconsistent suction. As pointed Zhou et al (2011), above models can be generalised by:

$$\frac{\mathrm{dS_r(s)}}{\mathrm{de}} = \mathrm{g}(\mathrm{s}, \mathrm{e}) \qquad \textbf{(2.4-6)}$$

where g is a general function. Also, temperature variation was not considered in those models.

2.5 *Effect of Temperature on SWCC Equations*

SWCC also can be affected by external factors such as temperature. Recently, research interest in soil's thermo-hydro-mechanical interactive behaviour is growing due to an increasing number of geotechnical problems involving thermal and unsaturated issues. For example, soils surrounding buried nuclear waste would certainly be casted into elevated temperature and partially saturated conditions. The earliest record about the thermal effect on hydraulic properties of soils was in 1937. At that time, Richards and Neal recorded capillary pressures declined when the soil was heated. In the past century, many researchers proposed a number of approaches to interpret the constitutive behaviour of unsaturated soils under different temperatures (Constantz 1981, Romero 1999, Masin 2011), in which the non-isothermal van Genuchten's model has been widely adopted to describe the dependency of SWCCs on the temperature. Unfortunately, the deformation caused by the temperature variation is usually neglected in this model. Even more recently, more and more researchers have come to realise the importance of understanding soil's thermo-hydro-mechanical interactive behaviour and have presented a few theoretical approaches. However, the current test results and theoretical investigation on the effect of temperature on water retention behaviour of deformable soils are still limited.

From 1950s to 1990s, the study of thermal effect on soil has been taken from a view of the temperature effect on capillary pressure. Gardner (1956) proposed a capillary pressure equation as shown below. Gardner found that coarse sand is able to maintain it water content at 2.2% when it was heated and cooled and suggested that the capillary pressure p_c decreases linearly when the temperature T increases.

$$\boldsymbol{p_c = a_{pc} + b_{pc}T} \tag{2.5-1}$$

where a_{pc} and b_{pc} are two empirical constants.

Philip and de Vries (1957) proposed an equation which consider the temperature effect on the capillary pressure during monotonic heating and cooling path under a constant water content w.

$$\boldsymbol{p_c(\frac{dp_c}{dT})^{-1} = \frac{a_{pc}}{b_{pc}} + T} \qquad \textbf{(2.5-2)}$$

Grant and Salehzadeh (1996) analysed capillary pressure function (CPF), and proposed a simple model which consider the temperature effects on CPFs. The model is derived from equation 2.5-2 with a variable β_0:

$$\boldsymbol{\frac{p_c(T)}{p_c(T_0)} = \left(\frac{\beta_0+T}{\beta_0+T_0}\right) = \left(\frac{a_{pc}+b_{pc}T}{a_{pc}+b_{pc}T_0}\right)} \qquad \textbf{(2.5-3)}$$

where $p_c(T)$ is the capillary pressure under observational temperature, $p_c(T_0)$ is the capillary pressure under the reference temperature T_0.

In the past decade, many researchers have proposed several models to interpret the unsaturated soil behaviour under different temperature, for example, Romero et al(1999); Wu et al (2004); Bolzon and Schrefler (2005); François and Laloui (2008); Masin and Khalili (2011).

Wu et al (2004) conducted a numerical modelling study on existing thermo-hydro-mechanical constitutive model for unsaturated soil and proposed an new equation based on the existing model. The authors pointed out that the suction decreases with increasing temperature under constant degree of saturation and the sensitivity expression of the suction with temperature change at certain constant water content value are:

$$\frac{\partial s(w)}{\partial T} = \frac{s(w)}{a_1+b_1T} \tag{2.5-4}$$

where T is temperature; s is suction; a_1 and b_1 are two empirical functions depending on water content w. To predict the suction development:

$$\frac{s(w,T)}{s(w,T_r)} = \left(\frac{a_1(w)+b_1(w)T}{a_1(w)+b_1(w)T_r}\right)^{b_1(w)} = \left(\frac{a_1+b_1T}{a_1+b_1T_r}\right) \tag{2.5-5}$$

where T_r is the reference temperature. As the author pointed out, the temperature is no the unique factor affecting the suction variation, especially during the high suction state. Combine equation 2.5-5 with Fredlund and Xing's equation 2.3-5, a new equation which representing a new retention curve between the degree of saturation and suction, and also considering temperature variation can be obtained as shown below:

$$\boldsymbol{S_{r,w} = C(s)\left(\frac{1}{1+(a_TS)^n}\right)^{m_r} r, a_T = a\left(\frac{a_1+b_1T_r}{a_1+b_1T}\right)^{b_1}} \tag{2.5-6}$$

where $S_{r,w}$ is the degree of saturation, α, m_r and n are the parameters which related to the air entry value, the residual water content and the slope of the suction-saturation curve at the air entry value of the soil; C(s) is a suction related parameter.

The isothermal van Genuchten model as shown in 2.3-4 combined with the non-isothermal van Genuchten model as shown below has been widely adopted by those researchers due to it simple form and less fitting parameter:

$$\boldsymbol{S_r = S_r^{res} + (1 + S_r^{res})\left(\frac{1}{1+\left({}^{s}/_{a_T}\right)^n}\right)^m} \tag{2.5-4}$$

$$a_{T=}a\frac{a'+b'T}{a'+b'T_0} \quad \textbf{(2.5-5)}$$

where, S_r^{res} is the residual degree of saturation and is usually considered as a constant value. However, the deformation caused by temperature variation is not considered in this non-isothermal van Genuchten model.

Very recently, more and more researchers realise the limitation of existing theoretical approaches: considering the effects of temperature only or considering the effects of deformation only. Salager et al (2010) proposed a theoretical approach based on the general law linking the variation in suction with water content, temperature and void ratio to model the thermal effect on water retention behaviour of deformable soils. However, as pointed out by Salager et al (2010), it is difficult to obtain experimental data for some functions which they employed in their approach for example the suction change due to the void ratio change.

François and Laloui (2008) proposed a unconventional constitutive model for unsaturated soil: ACMEG-TS. This approach is a unified thermo-mechanical modelling. The authors have employed the air entry value as a function into the proposed constitutive model. However, the air entry value is not employed in some popular used SWCC equation such as van Genuchten equation as shown in (2.3-4)(van Genuchten 1980) and Fredlund Xing's equation (Fredlund and Xing 1994) as shown in (2.3-5).

2.6 Deformation Behaviour for Soil

As mentioned previously, unsaturated soil consists of three phases: solid, water and air. Therefore, the deformation of unsaturated soil can be caused by pore-air variation, pore water variation (negative) and soil structure. Pore-water variation can be understood as the change of water content or degree of saturation. Soil structure, in other words, usually is taken as void ratio change. Pore-air variation is the difference between the above mentioned two.

The soil used in this research is reconstituted soil. As stated by sheng (Sheng 2011), this type of soil usually consists of two types of pores: large inter-aggregates pore or macro-pore and small intra-aggregates pore or micro-pore. Unsaturated soil with a bi-modal pore size distribution (PDS) is usually collapsible. This type of structure can be verified by using Scanning Elector Microscope (SEM) and Mercury Intrusion Porosimetry (MIP) methods. In this study, SEM method is used; please refer to chapter 3 for method explanation and results.

When unsaturated soil with a bi-modal PDS is experiencing the wetting process (or saturation process), it will lead to the collapse of the inter-aggregate pore and as a result, the soil will have a uni-modal pore size distribution. In another word, the soil structure can be influenced by the variation of it water content. In 1996, Delage et al (1996) conducted a study on the microstructure of compacted silt. The study shows that soil compacted under dry –optimum water content has a bi-modal PDS and a uni-modal PDS was found for soil compacted under wet-optimum water content. The same results were found by other researchers (Sivakumar and Wheeler 2000, Simms and Yanful 2001).

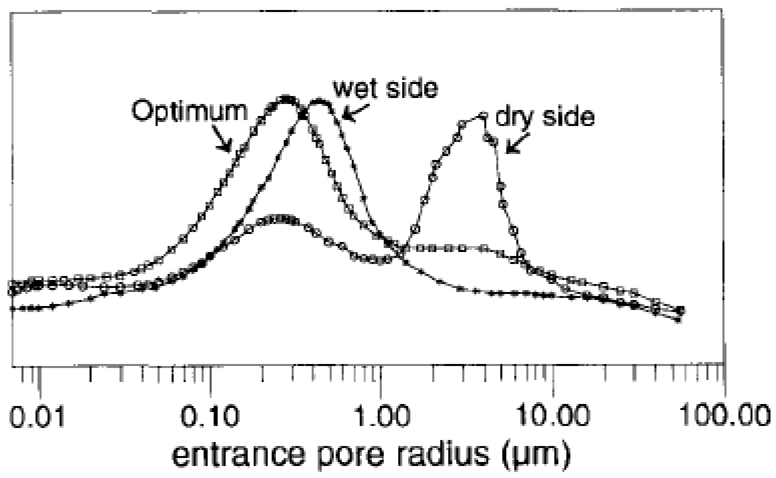


Figure 2.6.1-1 Pore size distributions for bimodal and uni-modal for compacted soil(Delage, Audiguier et al. 1996)

Discovered by many researchers, the presentence of macrospore is reducing with dry density of the soil, in other words, when external loading or internal matric suction varies, the voids between macrospore also varies. The microspore of the soil can be saturated. During wetting, the pore water pressure increases, it can expand the microspore. Therefore, macrospore and microspore are contributing to the deformation behaviour of the soil due to the drying or wetting process or in another word, matric suction variation.

As above, due to the potential instability of unsaturated soil, it can result in swelling or collapse during wetting, and shrink during drying. In another word, total volume change of unsaturated soil is varying with the matric suction.

In literature, the experimental study on the deformation behaviour of reconstituted soil is still limited.

2.7 Soil Suction Measurement

The development of suction theory can be traced back to 1907 by Buckingham, and not long after that, the importance of soil suction has been realised by many researchers (Garbulewski 1995, Delage, Howat et al. 1998, Sudhakar 2000, Sillers 2001). As point out by Fredlund and Rahardjo (Fredlund and Rahardjo 1993), soil suction is the free energy state of soil water.

The total suction ψ of a soil has two components, one is called matric suction, and the other one is osmotic suction.

$$\psi = (u_a - u_w) + \pi \tag{2.7-1}$$

where, ψ is the total suction, u_a is the pore-air pressure, u_w is the pore water pressure, $(u_a - u_w)$is the matric suction and π is the osmotic suction.

Osmotic suction is related to the salt in the pore water. If the salt content changes, it will affect the mechanical behaviour of the soil for example the shear strength of the soil. Matric suction can be affected by the environmental change. In geotechnical engineering, most unsaturated soil related problems are involve with environmental change, such as loss of soil strength due to the season (wet and dry) changes. As state by Fredlund and Rahardjo (1993), the osmotic suction change is generally less significant due to several reasons and it is not necessary to know the change in the osmotic suction. Therefore, in this research, any mention about suction means matric suction.

The measurement of matric suction can be done either in a direct or indirect way. For example high air entry value ceramic disk is a direct method. Different types of porous sensors can be used for indirect methods. In this research, the filter paper suction method for measuring suction has been conducted, and Psychrometer (WP4-T) for total suction measurement was also performed.

2.7.1 Filter Paper Suction Method

The filter paper suction measurement was developed in1920 and it was originally from Europe. From 1970s, the filter paper method has been used in soil science and geotechnical engineering (Fawcett 1967, McQueen 1968, McKeen 1980, Hamblin 1981, Chandler 1986, Chandler, Crilly et al. 1992, Ridley 1993, Houston, Houston et al. 1994, Marinho 1994, Marinho 2006).

Filter paper method can be used to measure both matric and total suction. Figure 2.7.1-1 below is shown both contact method for matric suction measurement and non-contact method for total suction measurement. On the bottom, a filter paper is in contact with the soil directly to allow the moisture content in the soil flow to the filter paper until they become equilibrium; this process is measuring the matric suction. On the top, there is a perforated disk in between soil and filter paper, therefore the water in the soil can only be transferred to the filter paper in the form of vapor until they become equilibrium; this process is measuring the total suction.

The test duration is from 7 days up to 14 days (ASTMD5298). At each equilibrium stage, the suction of the soil is equal to the suction of the filter paper, suction of the filter paper and the soil is equal, therefore the suction can be calculated.

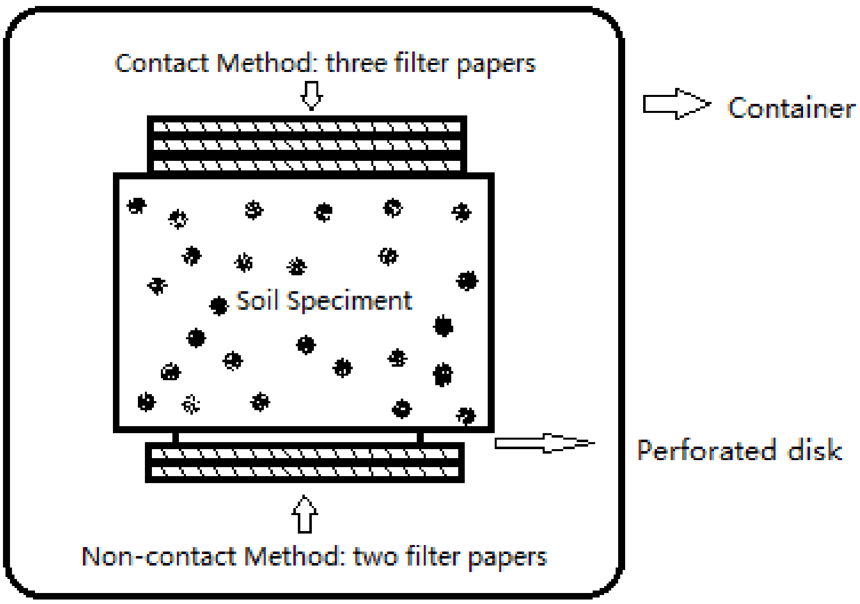


Figure 2.7.1-1 Contact method for matric suction measurement and Non-contact method for total suction measurement

2.7.2 Psychrometers

Psychrometers are designed for total suction measurement. In this research, Dew-point psychrometers-WP4 is used. WP4 has been commonly used by many researchers (Loiseau 2001, Leong, Tripathy et al. 2003, Tang and Cui 2005)

Figure 2.7.2-1 Dew-point psychrometers-WP4

The working principle is to measuring the relative humidity of the air inside the small sealed sample chamber. At equilibrium, the relative humidity of the air in the chamber is equal to the relative humidity of the testing soil. By using the psychometric law (Fredlund and Rahardjo 1993), the total suction can be calculated as :

$$\psi = -\frac{RT\rho_w}{M_w}\ln(RH) \qquad 2.7.2\text{-}1$$

$$RH = {}^{p}/_{p_0} \qquad 2.7.2\text{-}2$$

where p is the vapour pressure, p_0 is the relative to the saturation vapour pressure, R is the gas constant (8.314J/(mol K)), T is the absolute temperature, M_w is the molecular mass of water (18.016kh/kmol) and ρ_w is the density of pure water (998kg/m^3 at 293K).

WP4 can be affected by some factors such as the temperature. Therefore, the test should be conducted at a constant temperature environment. This is also applying the humidity as well. For calibration, a solution of 0.5M KCl is used in this research as suggested by the manufacturer. The result should be 2.19±0.1MPa at 25°C.

As pointed out by Vikas et al (2006), results of total suction measured by WP4 is still limited.

Chapter 3 EXPERIMENTAL INVESTIGATION

3.1 Introduction

In this chapter, the experimental methodology will be discussed in detail, includes the setting of the testing system and testing material properties, preparation and testing procedure and outcomes.

The soil which has been tested in this study can be referred to as reconstituted soil sample. Basically, the original soil – silt clay is collected from a field site then going through a reconstituted process. Please refer to detailed processes in section 3.4.2 of this chapter. It would take up to 3 weeks before the sample is ready for testing. The equipment used in the research is Fredlund SWCC device. Please refer to the next section of this chapter for detailed explanation.

Basic soil properties is tested to have a better understanding of the testing soil, includes, moisture content and plasticity index by preforming Atterberg limits test. Special attention also paid to the minerals in the testing soil by preforming X-Ray diffraction. Also Scanning

Election Miscopy was used, as the particle shape can also affecting tests result. Please refer to detailed explanation and result in the next few sections.

3.2 Apparatus Description

Fredlund SWCC device is used in this research. This device is designed for unsaturated soil, and it is usually use to obtain soil water characteristic curve (SWCC) for the testing soil. This testing apparatus is flexible with applying matric suction, at the same time following various stress paths.

Figure 3-1 showing below is the Fredlund SWCC system includes main pressure control panel and pressure booster, loading frame and temperature control system, dial gage, sample ring and removable high air entry value (HAVE) disk. The specifications of each main part are presented as follows:

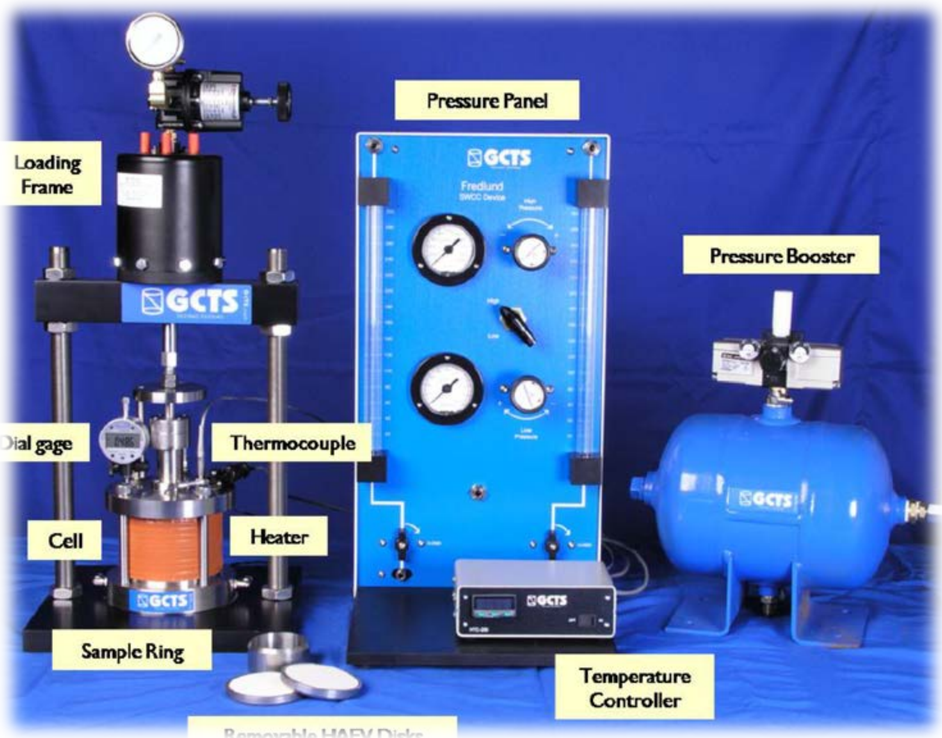


Figure 3.2-1 Fredlund SWCC system

a) SWC-150 Fredlund SWCC Pressure Control Panel:

The pressure control panel is for direct control of applied suction on the top of soil sample. The capability is up to 2000kPa. On the control, there are:

- Two opening valves on the top of the panel which allow diffused air to be flushed out.
- Two plastic reading tubes which measure the water content loose from the sample
- Two pressure regulators separated by high (2000kPa) and low (200kPa) pressure range which increase the accuracy of applied matric suction during testing.
- Two valves down the bottom of the panel which allow diffused water from the sample to flow out.

b) PCP- PBOOST Pressure Booster:

The booster is to pump the air pressure up to 2000kPa to supply the high suction requirement during the last stage of the test. Pumped air pressure can be holed by the blue tank underneath. The capacity is 3.8 liter. The booster used in this research requires compressed air source at 800 to 1000kPa.

c) SWC-PCA Pressure Cell Assembly

This assembly includes a stainless steel cell sealed by two O-rings pleased at both end, a load piston to apply vertical load and measure the deformation of testing soil, a specimen cutting ring with up to 71mm diameter and 50mm height and a 15 bar high air entry value ceramic disk mounted on stainless steel ring.

d) SWC- FRM Pneumatic Loading Frame

The loading frame is fitted with a pneumatic loader, a regulator and a dial-gauge. In this research, loading frame is used for the purpose of prepare soil sample with different initial densities.

e) GCTS HTC- 250 Temperature Controller

Generally, the temperature controller is used to maintain the cell temperature to prevent condensation of water vapour in the cell. In this research, temperature controller is used to generate a non-isothermal environment.

3.3 Apparatus preparation

Above mentioned apparatus are installed before testing. Two Fredlund SWCC systems are running at the same time by sharing one booster. Therefore, special installation method was designed for this experimental study as shown in Figure 3.3-1.

- During the low pressure stage (0 to 800 kPa), air compressor can fully supply the required air pressure without the booster. Therefore close valve 3 on the booster and open valve 2 and bottom valves behind the SWCC control panel.
- During the high pressure stage (above 800 kPa), booster needs to be used to pump air pressure up to a higher level. Therefore close valve 1, 2 and bottom valves behind the SWCC control panel, open valve 1 on the booster.

In the whole testing period, upper valves behind the SWCC control panel and valve 1 are remain of open.

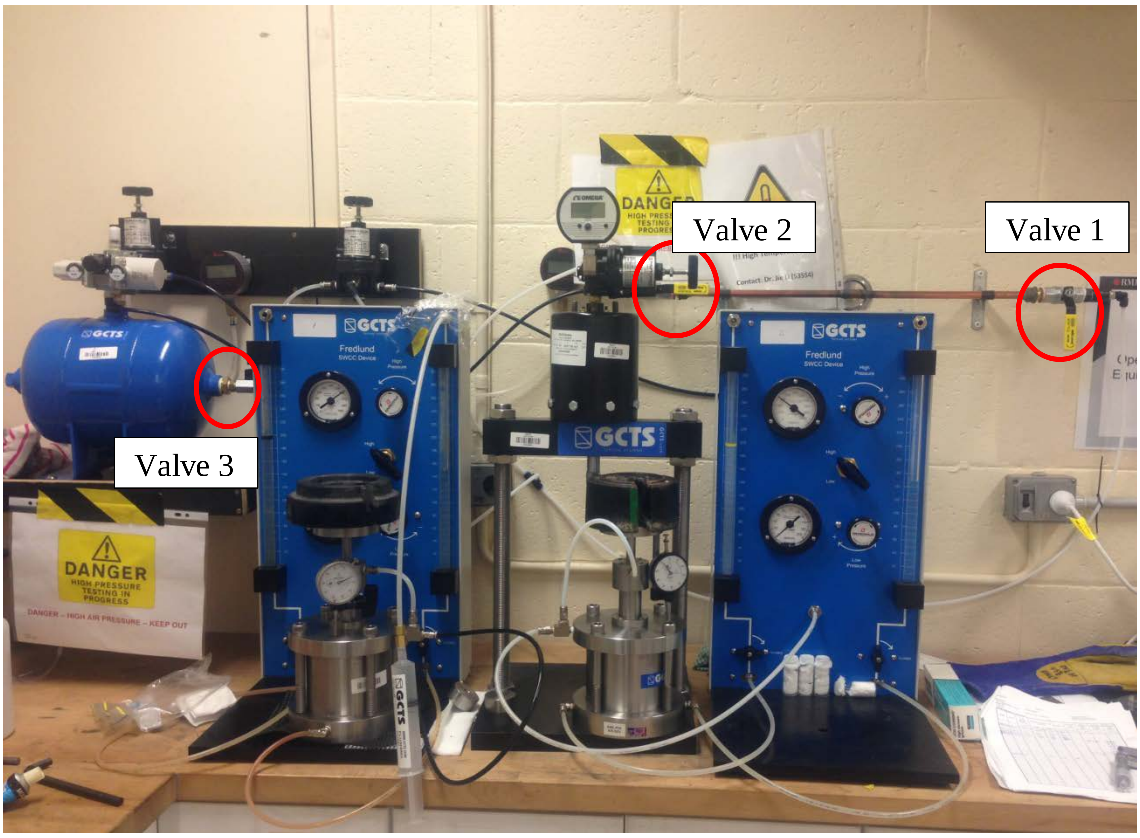


Figure 3.3-1 Fredlund SWCC system installation method

3.3.1 High air entry value ceramic disc saturation

High air entry value ceramic disc (HAVE) is a very important part in SWCC test. Whether it has been fully saturated will directly influence the SWCC test result. In this research, the HAVE ceramic disc has an air entry value of 1500 kPa. The method of saturation was adopted from Fredlund and Rahardjo (1993), the summarized procedures are as below:

- Place a brand new HAVE ceramic disc into a "locker-locker" container filled with distilled de-aired water overnight.
- Fill distilled de-aired water in the base pedestal of the pressure cell, and install the HAVE ceramic disc in the system, then continue to fill distilled de-aired water above till about half of the pressure cell.
- Close one valve down the bottom and leave the other one open, increase the air pressure to 600kPa, let the water flow through the disc for approximately 1 hour.

- Flush out the air bubbles collected below the disc, and then close both valves for approximately 1 hour. During this time, the air in the disc dissolves in the water.
- Then open one valve again for about 10mins to allow the water in the disc to flow out.
- Repeat abovementioned procedure six times, after which the HAVE ceramic disc is considering as fully saturated.

It is very important to ensure the HAVE ceramic disc remains covered with water all the time.

3.4 Testing Material

The soil used in this research can be referred to as unsaturated silt. As mentioned previously, unsaturated soil has a complex behaviour especially when its degree of saturation varies. Therefore, to help understanding the behaviour of unsaturated soil, some basic soil properties are studied. They can be taken as benchmarks.

3.4.1 Soil properties

3.4.1.1 Atterberg Limits

Atterberg limits test is one of the basic soil tests for soil classification. It is the primary form of classification for silt and clay soils. Atterberg limits test is composed of three parts: liquid limits test (AS 1289.3.1.2), plastic limits test (AS 1289.2.1.1) and shrinkage limits test (AS 1289.3.4.1).

Liquid limit is defined as the moisture content at which soil begins to behave as a liquid material. Liquid limit test is using one point casagrande method. As mentioned previously, the soil used in this research is silt, therefore, in theory two halves of silt cakes on liquid limit apparatus will flow together by 25 blows. The minimum depth of the sample in the apparatus should be 1 cm and palette knife should be used to cut the sample so the distance between two soil cakes is 10 mm. When the test is in process, the crank handle of the apparatus should be turned at 2 rev/sec.

Figure 3.4.1-1 Liquid limit test

The liquid limit w_L can be determined based on Australia standard AS 1289.3.1.2:

$$w_L = w(\frac{n}{25})^{tan\beta} \quad (3.4.1.1\text{-}1)$$

Where w is the moisture content, n is number of blows to closure and tanβ= 0.091 for a range of Australian soils. The result of liquid limit test is:

Table 3.4.1-1 Liquid limit test result

Liquid Limit, LL	
Number of blows	**25**
Tin no	1
Wet Soil + Tin(g)	58.62
Dry Soil + Tin(g)	45.01
Tin(g)	14.62
Moisture Content (%)	44.78
Liquid Limit w_L (%)	**44.78**

Plastic limit is the moisture content at which soil begins to behave as a plastic material. It can be determined by rolling a small clay sample into threads and finding the water content at which threads approximately 3mm in diameter will just start to crumble(Budhu 2007). According to Australia standard 1289.3.2.1 – 2001, take about 8 gram of the soil and roll it with fingers on a glass plate. The rate of rolling should be between 80 to 90 strokes per minutes. Collect and keep the pieces of crumbled soil thread into a tin and use to determine the moisture content.

Figure 3.4.1-2 Plastic Limit Test

The plastic limit w_p can be calculated based on Australia standard AS 1289.3.2.1:

$$w_p = \frac{m_b - m_c}{m_c - m_a} \tag{3.4.1.1-2}$$

Where m_b is the mass of container and wet soil, m_c is the mass of container and dry soil and m_a is the mass of container. The plastic limit test result is:

Table 3.4.1-2 Plastic limit test result

Plastic Limit, PL	
Number of blows	**25**
Tin no	2
Wet Soil + Tin(g)	25.7
Dry Soil + Tin(g)	23.09
Tin(g)	14.73
Plastic Limit w_p (%)	**31.22**

Shrinkage limit is present, the amount of water required to fully saturated the soil. It can be determined by measuring the horizontal shrinkage of the soil specimen in a shrinkage mould after oven dry 3 daya at 105°C.

Figure 3.4.1-3 Linear Shrinkage Test

The shrinkage limit LS can be calculated based on Australia standard AS 3.4.1:

$$\mathrm{LS} = \frac{L_S}{L} \times 100 \qquad (3.4.1.1\text{-}3)$$

Where, L the length of the mould and L_s is the longitudinal shrinkage of the specimen. The result is summarised below:

Table 3.4.1-3 Linear shrinkage test result

Linear Shrinkage LS	
Mould Length, L (mm)	250
Longitudinal shrinkage, L_s (mm)	205
Linear Shrinkage, LS =	**18%**
Mould weight (g)	173.36
Mould + Soil (wet) (g)	274.56
Mould & Soil (dry) (g)	243.81
Water Content (%)	**43.6%**

The plastic index I_p is another important index for soil classification. It can be calculated as the difference between the liquid limit and the plastic limit, therefore PI= 14%.

In summary, above results can be analysed using AASHTO Soil Classification System. Results were plotted on the plasticity chart as shown below. Hence, the testing soil in this research can be described as low plasticity Silt.

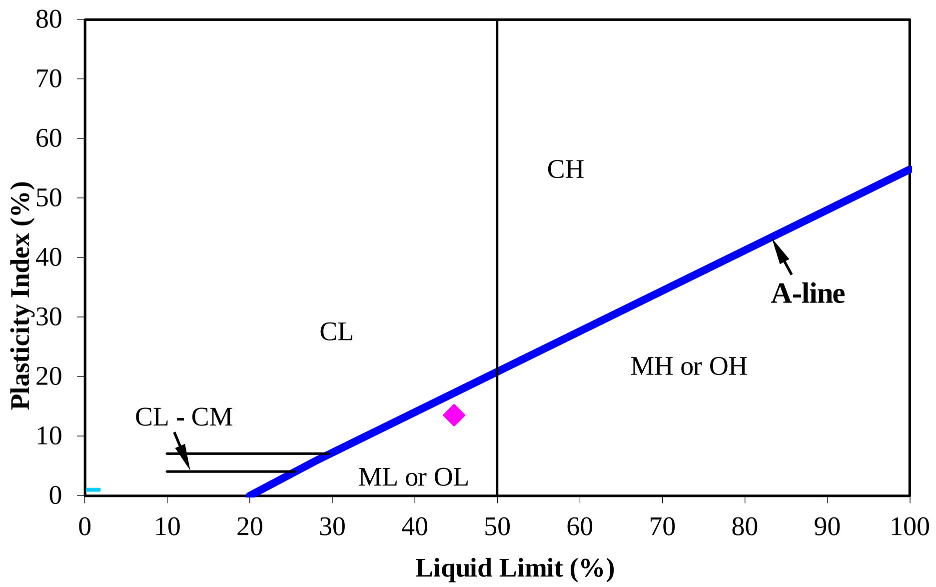


Figure 3.4.1-4 Plasticity chart

3.4.1.2 X-Ray Diffraction

Minerals play a significant role in soil formation. Some minerals may strongly influence the behaviour of soil. Therefore mineralogy of soil is commonly studied before soil testing. X-Ray diffraction (XRD) is a reliable technique of qualitatively identifying different minerals in the soil. As unsaturated soil has a complex behaviour, it is very important to investigate the composition of mineralogy in the testing soil.

The result of X-ray diffraction pattern for soil sample is shown in Figure 3.4.1.2-1. X-ray spectra were obtained using a Bruker D8 Advance system under the following conditions: CuKα radiation and 40 kV, 35 mA, step scan mode and step size 0.05°.

Using the search match technique, quartz was found (2θ: 21°, 27°, 50°) in the sample tested.In search/match technique of minerals, a peak of high intensity was considered in finalising and claiming the presence of candidates. It should be also noted that there are no significant amount of other minerals present in the sample tested. However there could be some trace elements (between 5 and 10 %) present in the sample.

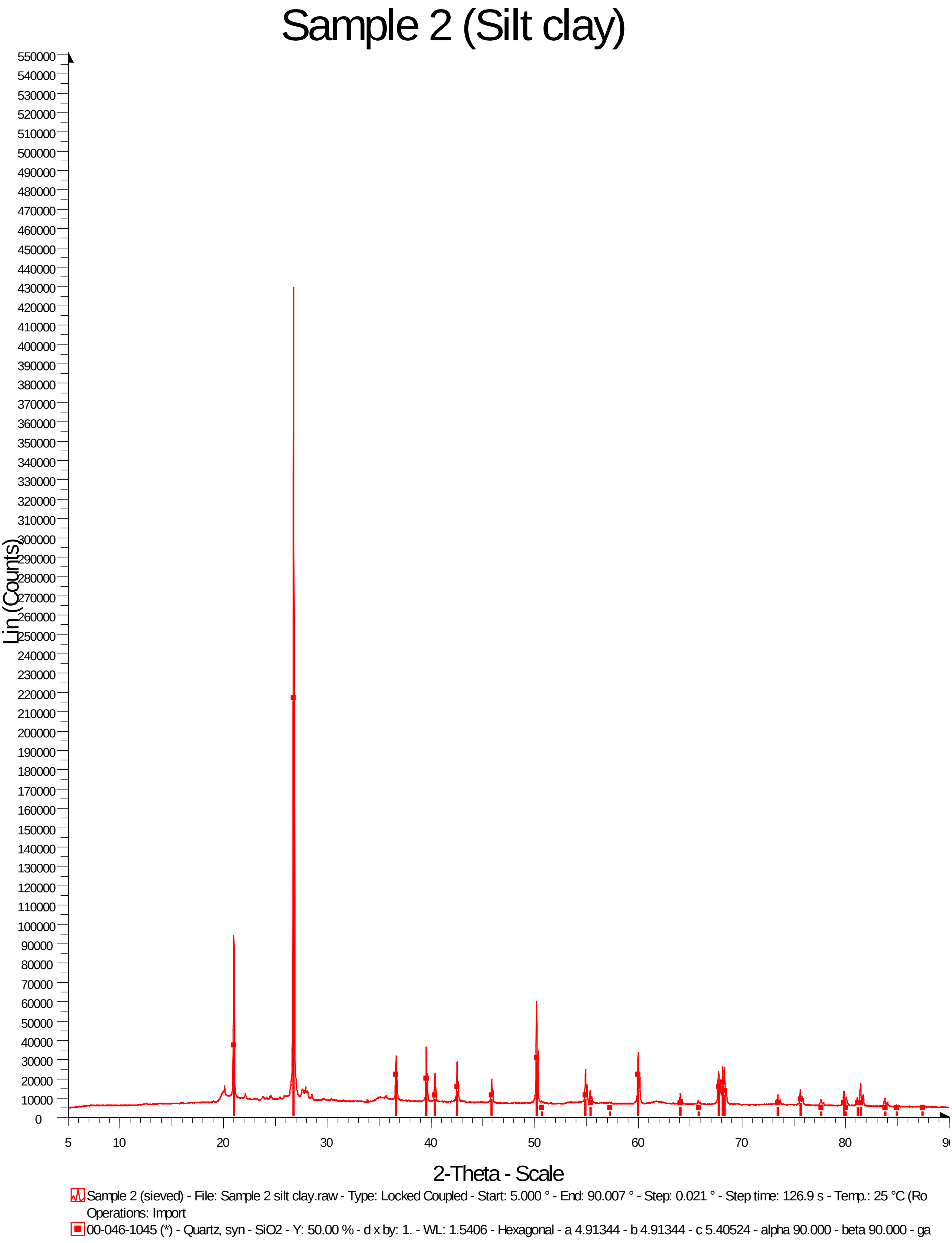


Figure 3.4.1-5 X-Ray Diffraction Result

3.4.1.3 Particle size analysis

Particle size analysis for soil is another regular test which provides information about soil's particle size distribution. The test result can be used directly for soil classification. In this research, the sample was analyzed using a Mastersizer 2000 (Malvern Instruments, UK) particle size analyzer with measurement range 0.02 to 2000 µm. The mass of the sample was about 50 mg. Samples were tested in the dispersion unit at 100 % (this means 100% ultrasound,1000 rpm stirrer speed and 2500 rpm pump speed) and allowed the samples to circulate for 1 minute before beginning measurement. Sample is identified as "Kaolinite low" in the software with preset particle refractive index value of 1.533. Figure 3.4.1.3-1 below shows the result of particle size analysis and Table 3.4.1.3-1 gives the detailed summary. (Note: particles larger than 150µm were sieved and separated from the test samples).

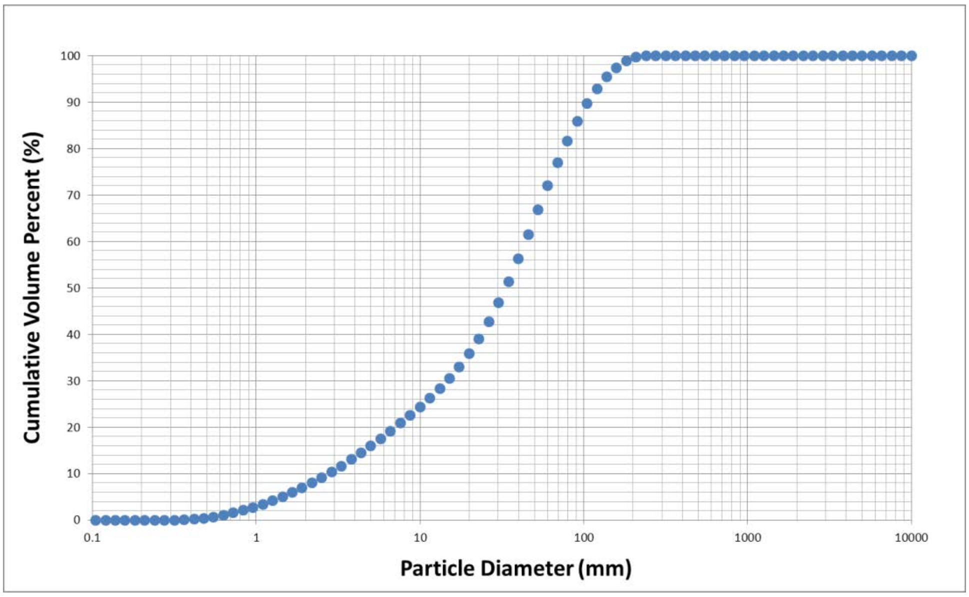


Figure 3.4.1-6 Particle Size Distribution

Table 3.4.1-4 Particle Size Distribution

Fraction	Particle size limits	Percentage (%)
Clay	< 2μm	6.93
Fine silt	6 μm to 2 μm	12.27
Medium silt	20 μm to 6 μm	16.62
Coarse silt	60 μm to 20 μm	36.19
Fine sand	200 μm to 60 μm	27.72

To classify the testing soil, not only particle size analysis result was used, but also Australia standard AS 1289.3.6.1-2009 was compiled and the unified soil classification system was adopted. From Figure 3.4.1-7 , silt content was 65.078 %, in amount of that, 36.189 % of silt particles are in the range of 60 μm to 20 μm (coarse silt). 27.715 % of particles belong to fine sandy group and 6.929% of particles are clay. The uniformity coefficient C_u can be calculated as:

$$C_u = \frac{d_{60}}{d_{10}} = \frac{0.48}{0.0025} = 19.6 \qquad (3.4.1.3\text{-}1)$$

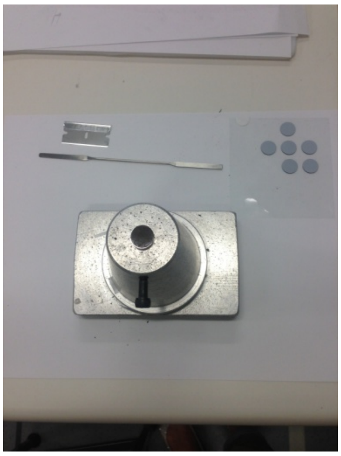
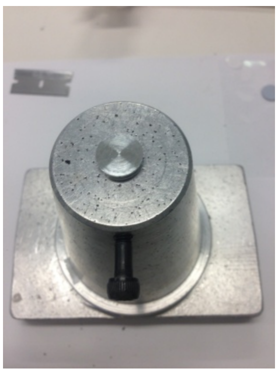
As above, the soil can be classified as well-graded silt.

3.4.1.4 Scanning Electron Microscope

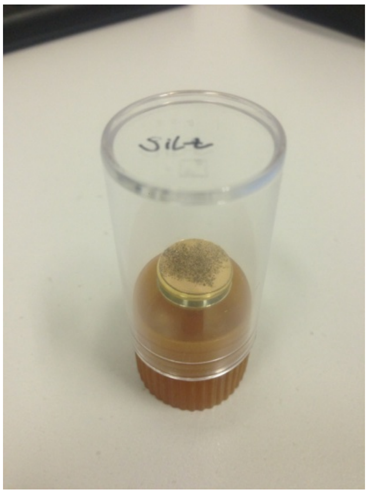
Scanning Electron Microscope (SEM) produces images of soil sample by scanning it with the focused electrons beam. In general, the working principle of SEM is the focused beam of electrons interacts with electrons in the sample and produce different signals that can be detected. The signals consist of following information: surface topography and composition of the testing sample. The main purpose of conducting SEM in this research is to identify the particle shape.

Before the sample can be put into specimen chamber for scanning, it must be prepared in the preparation laboratory. The procedures are shown below:

Table 3.4.1-5 SEM Sample Preparation

	SEM Preparation Laboratory
	Main tools for sample preparation: • aluminium pin stub • stub holder • carbon tab • spatula
	Secure the stub on the holder

	Collect a small amount of sample using spatula; Apply a thin layer of sample onto the carbon tab. Gently tap the stub on the bench to remove excess sample then blow away excess sample using an air duster.
	Now the sample is ready for coating using gold coater as shown on the left.
	Release the vacuum by loosening the glass chamber valve, open the top cover and place the sample in the chamber. Tighten the glass chamber valve and the gas leak valve and switch on “power” on SPI-Module Control. Wait until 2 millibar vacuum achieved then switch on “power” of sputter coater. Set timer to 30 seconds. Ensure “ready” light is on. Press “strat”, a purple light from the sample should be observed.

	Release the vacuum by loosening the glass chamber valve.
	Finished gold coated sample.

The finished gold coated sample now is ready for scan. The instrument which has been used here is Philips XL 30 Scanning Electron Microscope.

Figure 3.4.1-8 Philips XL 30 Scanning Electron Microscope

Figure 3.4.1.4-2 to Figure 3.4.1.4-4 below are the SEM result image obtained from the soil sample in different scales.

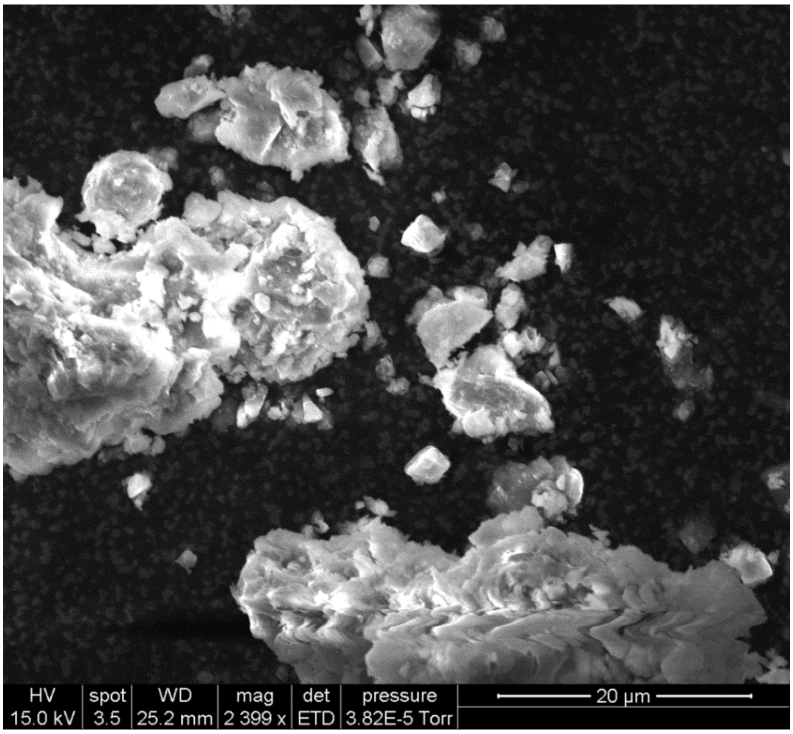


Figure 3.4.1-9 SEM result image -20um

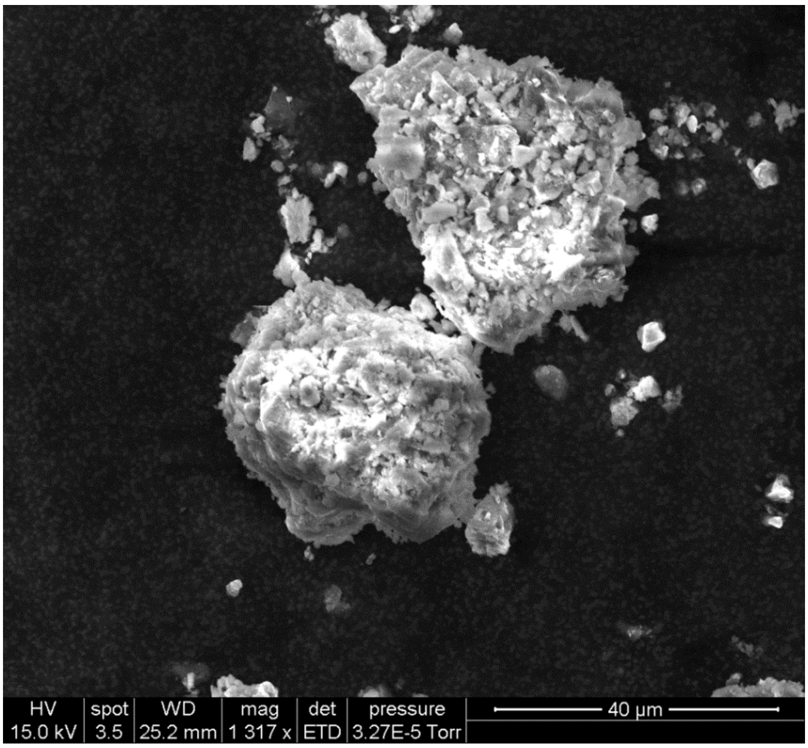


Figure 3.4.1-10 SEM result image- 40um

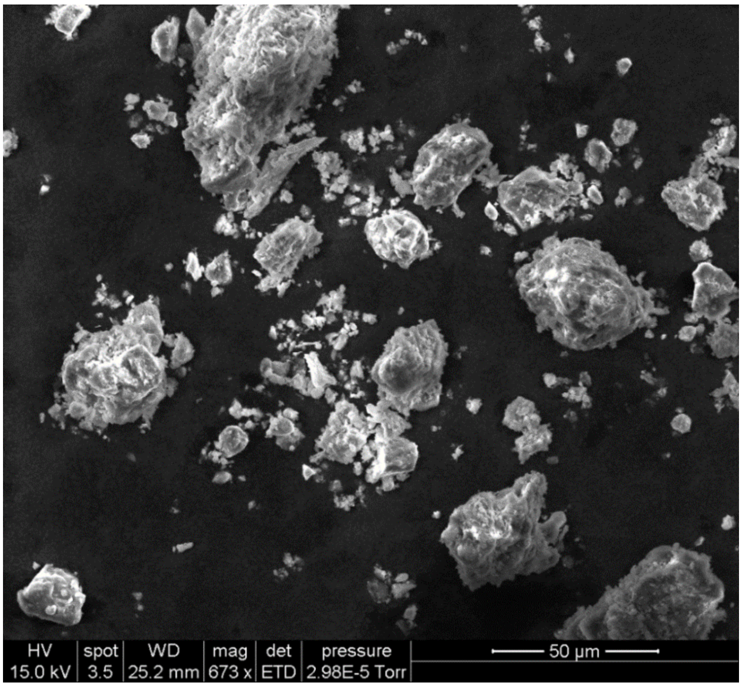


Figure 3.4.1-11 SEM result image- 50um

Figure 3.4.1.4-5 is a result image in 10μm, as can be seen clearly that the particle has a plate shape.

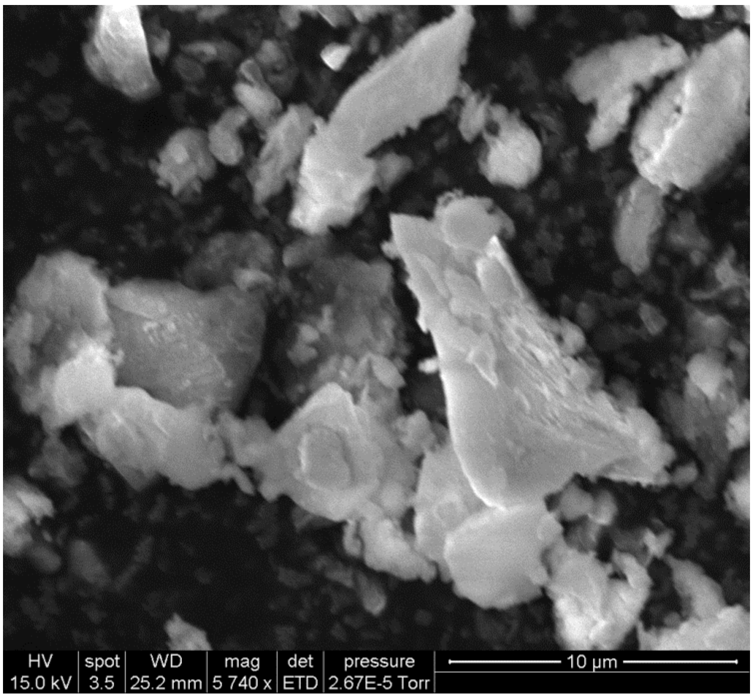


Figure 3.4.1-12 SEM result image- 10um

3.4.2 Sample preparation -Reconstitution process

In current practice, two types of soil samples are often in use in the laboratory: compacted and reconstituted soil sample. Literature review indicates that most available experimental data are based on compacted soils because it is far easier to prepare a compacted soil sample than a reconstituted soil sample. However, it would be more appropriate to use reconstituted soil as the testing material. This is primarily because the stress history of the soil has been removed after reconstitution processes where compacted soil sample would still have it stress history. Also, it will remove any previous exceeded factors which could influence the experimental result. Thus, reconstitution processes is a more precise method to simulate the soil under a natural state, yielding more reliable results.

As stressed by Sheng (2011), compacted soils usually have a double-porosity microstructure, which means there are two types of pores in those soils: large and small intra-aggregates. This type of soil is collapsible due to the unstable large intra- aggregates. Reconstituted soils usually have a uni-modal pore size distribution. This type of soil usually does not cause volume collapse under constant stress. However, the SFC model proposed by Sheng et al (2008) indicated that a reconstituted soil can evolve into a bi-modal collapsible soil (compacted soil) if the soil is dried and compressed to adequately high stresses. However, in the literature, available experimental data on reconstituted soils is too few to conclude this evolution but the limited data seem to be supportive. Therefore, it is beneficial to use reconstituted soil as the testing material.

Hence, the reconstituted soil samples are used in this research. The following steps were taken to reconstitute soil sample:

1. The original soil is from a field site at Glenroy, in a northern suburb of Melbourne. The soil is collected from a depth of approximately 0.5 meter because the top 0.3 to 0.5 meter of soil might contains vegetation and other artificial martial.

Figure 3.4.2-1 Testing Soil Collection

2. Afetr being transported to the laboratory, the collected soil was place into an oven at 105°C, drying for 3 days.

3. Dried soil was then smashed by using Los Angeles Abrasion Machine.

4. The smashed soil came out in a relatively small partial size; they are now ready to be sieved through 150µm screen. This step is to remove any leftover coarse materials and vegetation.

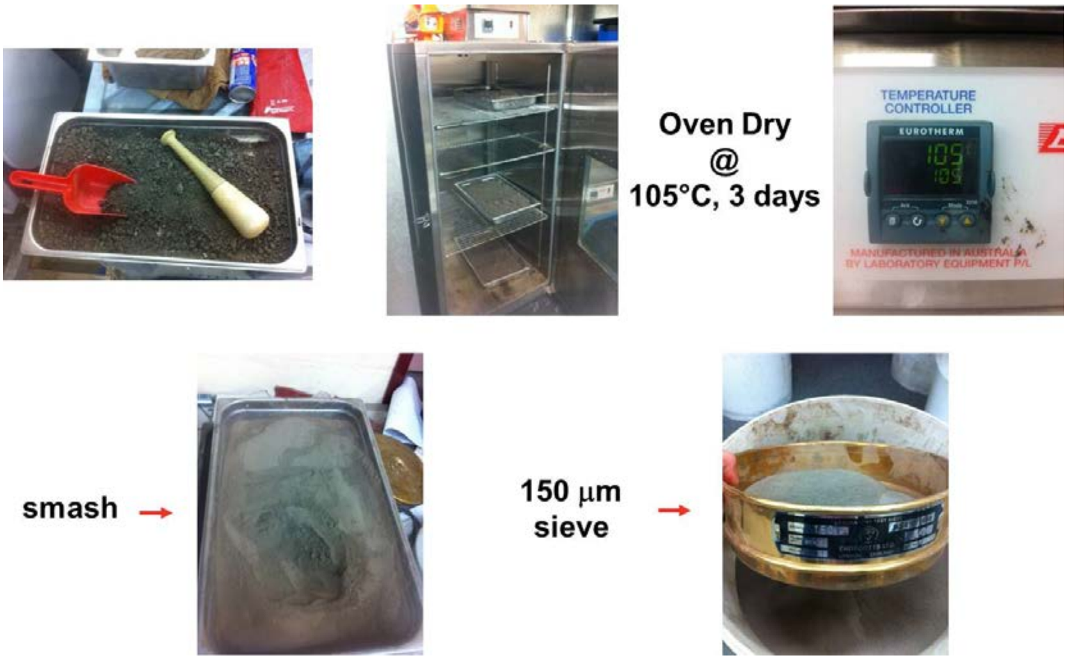


Figure 3.4.2-2 Sample Preparation in the Laboratory

5. The distilled water was added into the soil passed through the sieve in a rotary mixer. This step took about3 hours until sieved dry soil powder became smooth slurry.

6. The slurry is then placed into a pre-consolidation cell with approximately 55kPa vertical pressure for about 3 weeks before it is ready for testing.

Figure 3.4.2-3 Pre-consolidation cell

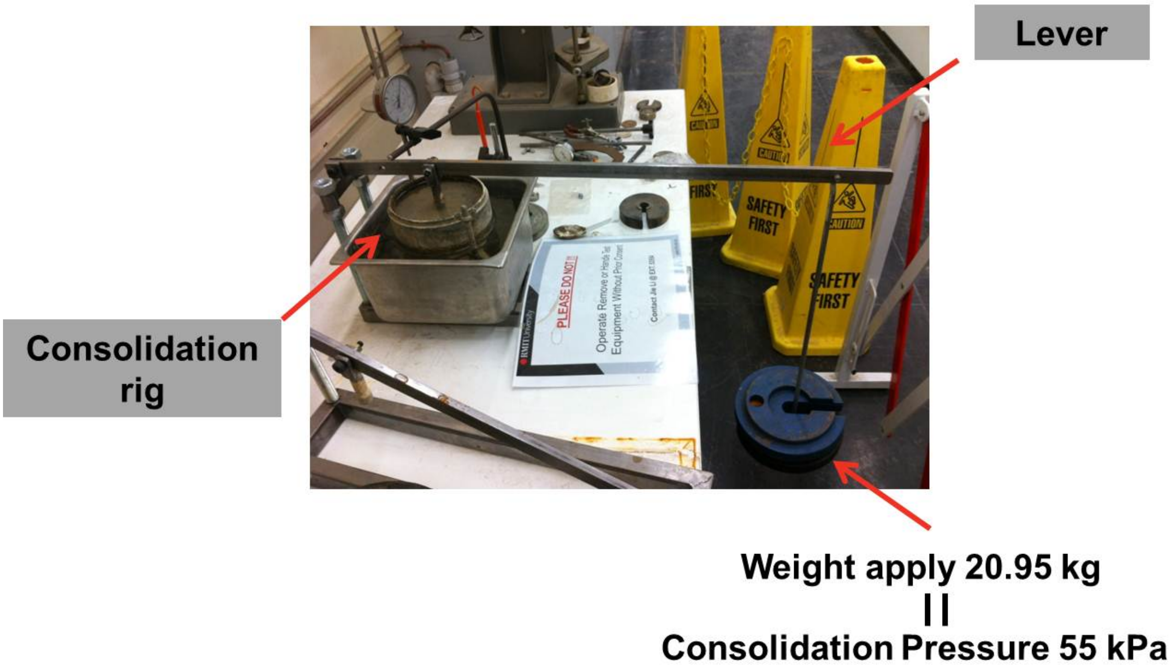


Figure 3.4.2-4 Consolidation Rig (Special made for this research)

Water content test for reconstituted soil sample is performed immediately to calculate the degree of saturation. If it less than 100%, pre-saturation process will be performed at the beginning of the SWCC test.

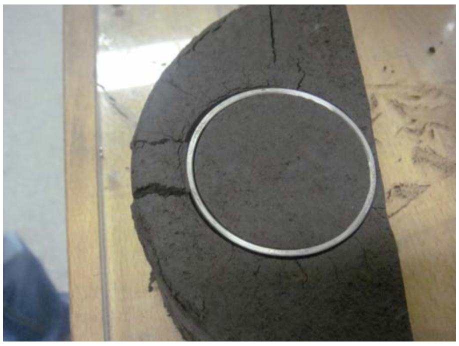
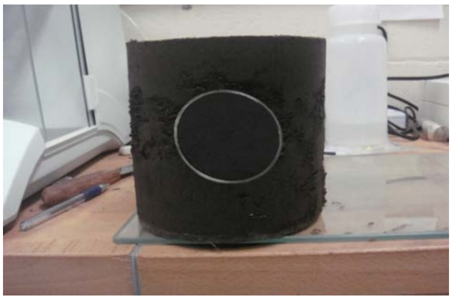
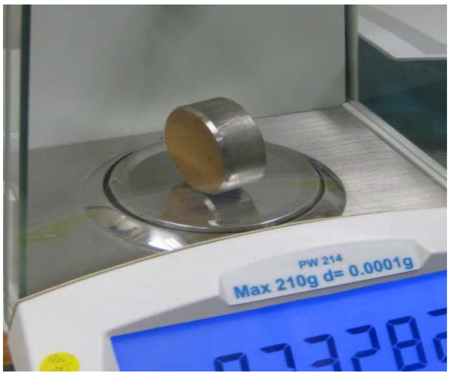
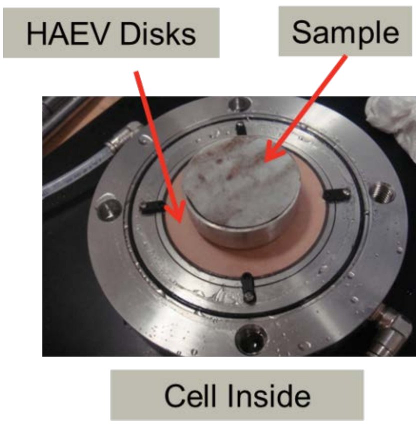
3.5 Testing procedure

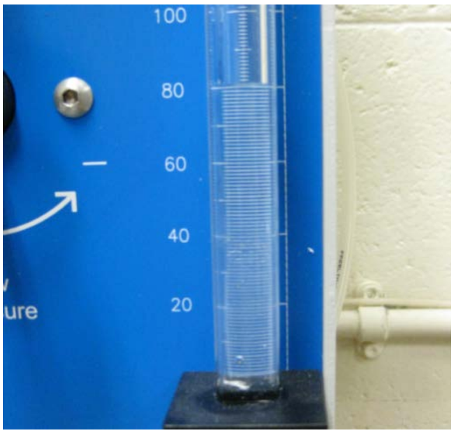
In this study, two types of SWCC test were conducted: conventional and non-isothermal. The conventional SWCC device is showing below on the left. The main control panel of the non-isothermal SWCC device is the same but with the additional heating pad attached on the sample cell as shown below on the bottom right and a temperature controller shown on the top right.

Figure 3.4.2-1 Fredlund SWCC system with Temperature Controller

The summarised procedure is shown as below:

Table 3.4.2-1 SWCC Testing Procedure

	SEM result determines that soil sample particles are in a plate shape. Therefore, by cutting from the top or from the side could influence the final SWCC curve. The figure on the right is cutting sample from the top.
	Cutting the sample from the side
	Weight the sample
	Place sample into the SWCC cell

	A digit dial gauge was used to measure the vertical displacement of the soil specimen so that the volume change and void ratio of the specimen can be calculated.
	A water volume change indicator was used to measure the water discharged out of the specimen
	Also, at the end of each stage, sample was taken out from the SWCC device to measure the weight lost

	The change in height and diameter was measured as well.

Before each test, basic soil properties such as the initial mass of the sample m_0 and the initial sample volume V_0 are measured and recorded. Initial water content w_i and initial void ratio e_0 of specimen are calculated. Therefore, initial water mass, m_w^0, initial water volume V_w^0, the mass of soil particles m_s and the volume of soil particles, V_s , can be obtained. The mass of soil particles m_s and the volume of soil particles V_s are considered as two constant numbers.

Once the test started, basic information of:

- the water discharge Δm_w can be obtained: (1) using a water volume change reading tube, locate on the main Fredlund SWCC device control panel; (2) the weight loss of the sample measurement at the end of each stage.
- vertical displacement ΔH ($\Delta V = \Delta H \times cross - section$) can be obtained: (1) using the dial gauge with a resolution of 1 μm located on the top of the sample cell ; (2) sample deformation measurement at the end of each stage.

Then variables required to obtain the SWCC curve can be calculated by using equations below:

- The new water mass m_{w_n}:

$$m_{w_n} = m_{w_{m-1}} - dm_w \qquad 3.5\text{-}1$$

- The change of water volume dv_w:

$$dv_w = \pi r^2 dh \qquad 3.5\text{-}2$$

- The new volume after each testing stageV_{sample_n}:

$$V_{sample_n} = V_{sample_{n-1}} - dv_w \qquad 3.5\text{-}3$$

- The new void ratio e_n:

$$e_n = (v_{sample_n} - v_s)/v_s \qquad 3.5\text{-}4$$

- The new water content w_n%:

$$w_n = m_{w_n}/m_s \qquad 3.5\text{-}5$$

The degree of saturation S_r:

$$S_r = \frac{w_n - G_s}{e_n} \qquad 3.5\text{-}6$$

After the calculation of the new water content, w_n, new void ratio, e_n and the degree of saturation S_r, the relationships between *w vs* ln*s* and S_r *vs* ln*s*, and *e vs* ln*s* can be obtained.

Before testing, the reconstituted soil sample was carefully trimmed to size and weighted. All initial parameters are recorded. The initial water content is calculated by using the oven dry method. A 20 kPa setting pressure is applied gradually to the specimen and kept constant throughout the SWCC test.

The maximum matric suction allowed for the SWCC testes is limited to 1500 kPa due to the air entry value of the HAEV ceramic stone. In this study, the suction range above 1500 kPa (i.e., total suction) was measured by using the Dewpoint Potentiometer (WP4) and the filter paper method. Van Genuchten equation(1980) was used in this study as it has been proven to be the best fitting equation for SWCC of unsaturated soils.

3.5.1 Stage 1 – SWCC test under constant temperature and vertical pressure

In Stage 1, three conventional SWCC tests were conducted to study the water retention behaviour of testing samples. Results are also used as benchmarks for the non-conventional SWCC test in stage 2 and 3.

Sample 1: Silty clay at the Glenroy test site Victoria; initial void ratio = 0.79, initial water content = 29.3%. Duration: 28/01/2012 to 17/04/2012

Table 3.5.1-1 Initial condition of SWCC test -stage 1 sample 1

Initial parameters	*Number*
Specimen height h	19.8 mm
Specimen diameter D_{ring}	50.2 mm
Mass of specimen m_0	73.1g
Water content w_i	29.3%

Mass of soil particles m_s	57.5g
Volume of soil particles V_s	21299 mm^3
Mass of water m_w^0	15.6g
Initial void ratio e_0	0.79

Table 3.5.1-2 Water discharge and calculation of water content -Stage 1, Sample 1

Suction (kPa)	Sample mass after each stage (g) (Ring weight included)	Water discharge (cc)	Weight of water, Ww (g)	Water content (%)
1	115.67	0	16.85	**29.30**
20	114.88	0.79	16.06	**27.92**
50	113.77	1.11	14.95	**26.00**
100	112.79	0.98	13.97	**24.30**
200	111.30	1.49	12.49	**21.71**
400	109.68	1.63	10.86	**18.89**
800	107.63	2.05	8.81	**15.33**
1400	107.25	0.38	8.43	**14.66**

Table 3.5.1-3 Volume change and calculation of void ratio and Degree of saturation- Stage 1, Sample 1

Suction (kPa)	Vertical deformation (mm)	Disp. volume (mm^3)	Total Volume (mm^3)	e = $(V-V_s)/V_s$ assuming A=Const	S_r (%)
1	0	0	38132.26	**0.79**	**100.00**
20	0.190	375.98	37756.28	**0.77**	**92.64**
50	0.160	316.61	37439.66	**0.76**	**87.33**
100	0.2	395.77	37043.89	**0.74**	**80.32**
200	0.23	455.13	36588.76	**0.72**	**71.88**
400	0.22	435.34	36153.42	**0.70**	**59.25**
800	0.118	233.50	35919.91	**0.69**	**56.83**
1400	0.02	39.58	35880.34	**0.68**	**56.81**

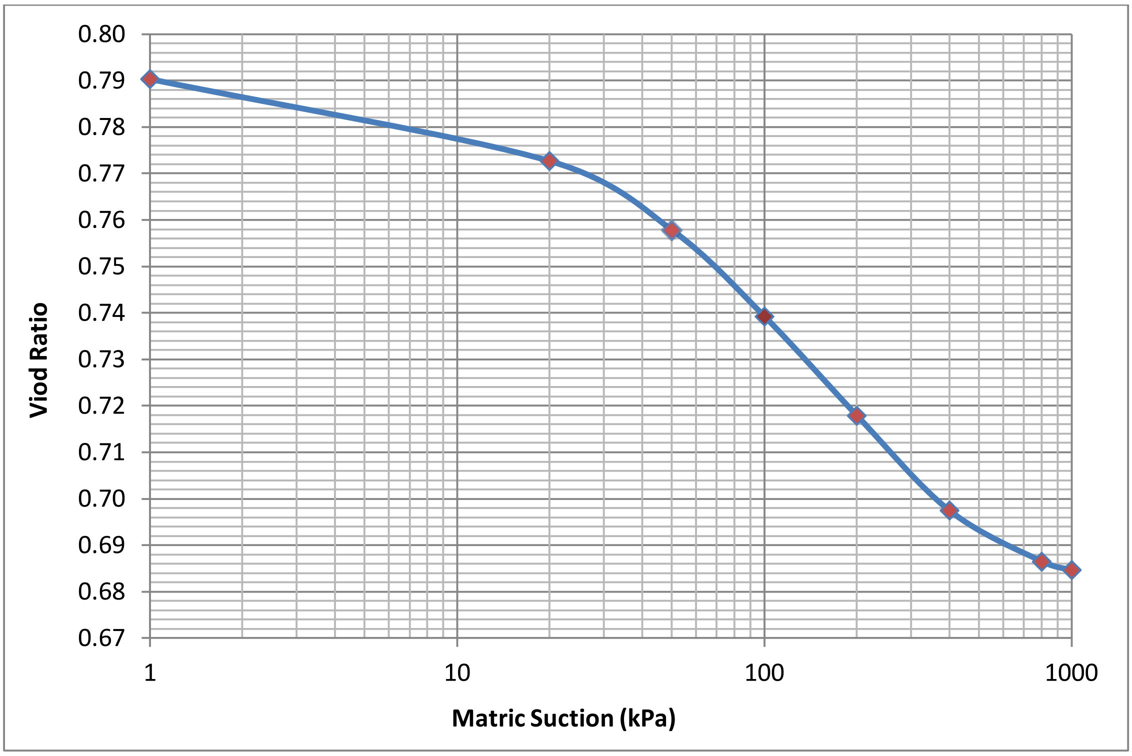


Figure 3.5.1-1 SWCC Test Stage 1, Sample 1 - $e - \ln s$ curve

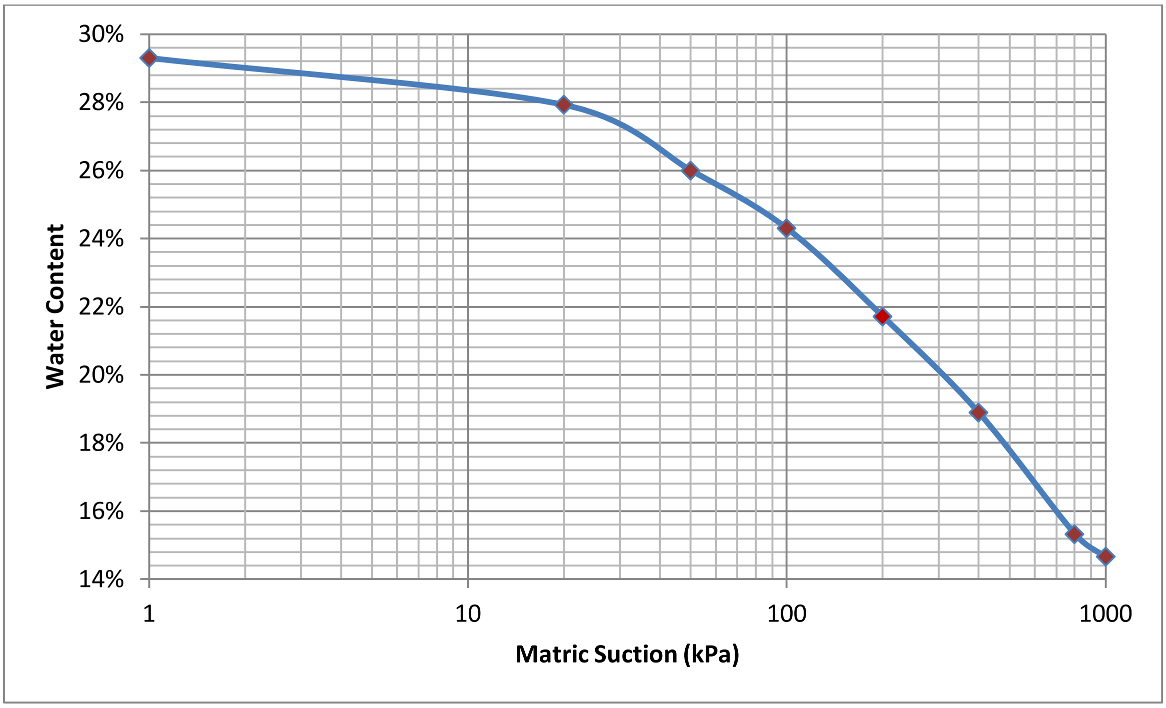


Figure 3.5.1-2 Volumetric water content *versus* soil suction - Stage 1, Sample 1

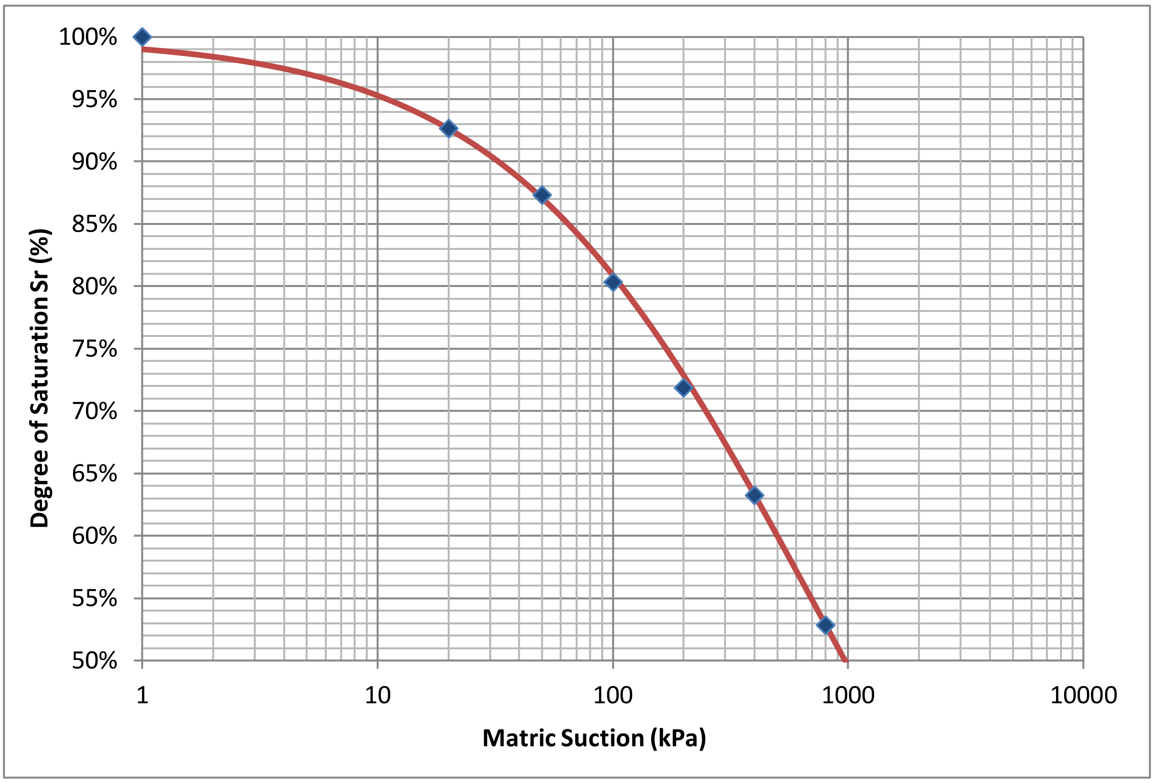


Figure 3.5.1-3 SWCC Test Stage 1, Sample 1- degree of saturation *versus* soil suction (Van Genuchten equation: a = 400, m = 0.7, n = 0.66)

Sample 2: Silty clay at the Glenroy test site; initial void ratio = 1.13, initial water content = 36.24%. Duration: 06/06/2012 to 27/07/2012

Table 3.5.1-4 Initial condition of SWCC test -stage 1 sample 2

Initial parameters	*Number*
Ring height h	20.03 mm
Ring diameter D_{ring}	50.16 mm
Mass of specimen m_0	68.97g
Initial water content w_i	36.24%
Mass of soil particles m_s	50.27g
Volume of soil particles V_s	18619 mm^3
Mass of water m_w^0	18.69g
Initial void ratio e_0	1.13

Table 3.5.1-5 Water discharge and calculation of water content -Stage 1, Sample 2

Suction (kPa)	Sample mass after each stage (g) (Ring Weight included)	Water discharge (g)	Weight of water, Ww (g)	Water content (%)
1	111.55	0	18.22	**36.24**

20	112.58	-1.03	19.25	**38.29**
50	110.80	1.78	17.47	**34.75**
100	109.45	1.35	16.17	**32.05**
200	107.59	1.85	14.26	**28.37**
400	106.19	1.41	12.86	**25.57**
800	104.42	1.76	11.09	**22.07**
1400	103.11	1.31	9.78	**19.46**

Table 3.5.1-6 Volume change and calculation of void ratio and Degree of saturation- Stage 1, Sample 2

Suction (kPa)	Vertical deformation (mm)	Disp. volume (mm^3)	Total Volume (mm^3)	$e = (V-V_s)/V_s$ assuming A=Const	S_r (%)
1	0	0	39584.87	**1.126**	**100.00**
20	0.22	434.78	39150.08	**1.10**	**93.75**
50	0.38	750.99	38399.10	**1.06**	**88.32**
100	0.254	501.97	37897.12	**1.03**	**83.60**
200	0.268	529.64	37367.48	**1.01**	**76.08**
400	0.188	371.54	36995.94	**0.99**	**69.96**
800	0.24	474.31	36521.63	**0.96**	**61.97**
1400	0.056	110.67	36410.96	**0.956**	**54.99**

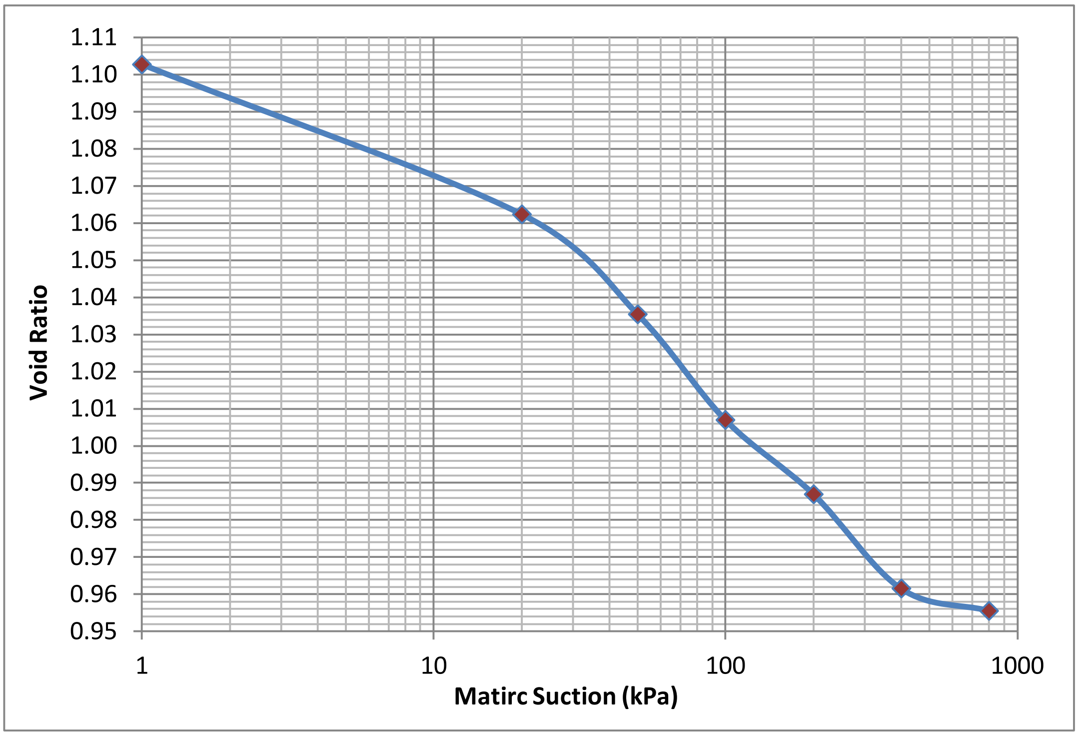


Figure 3.5.1-4 SWCC Test Stage 1, Sample 2 - $e - \ln s$ curve

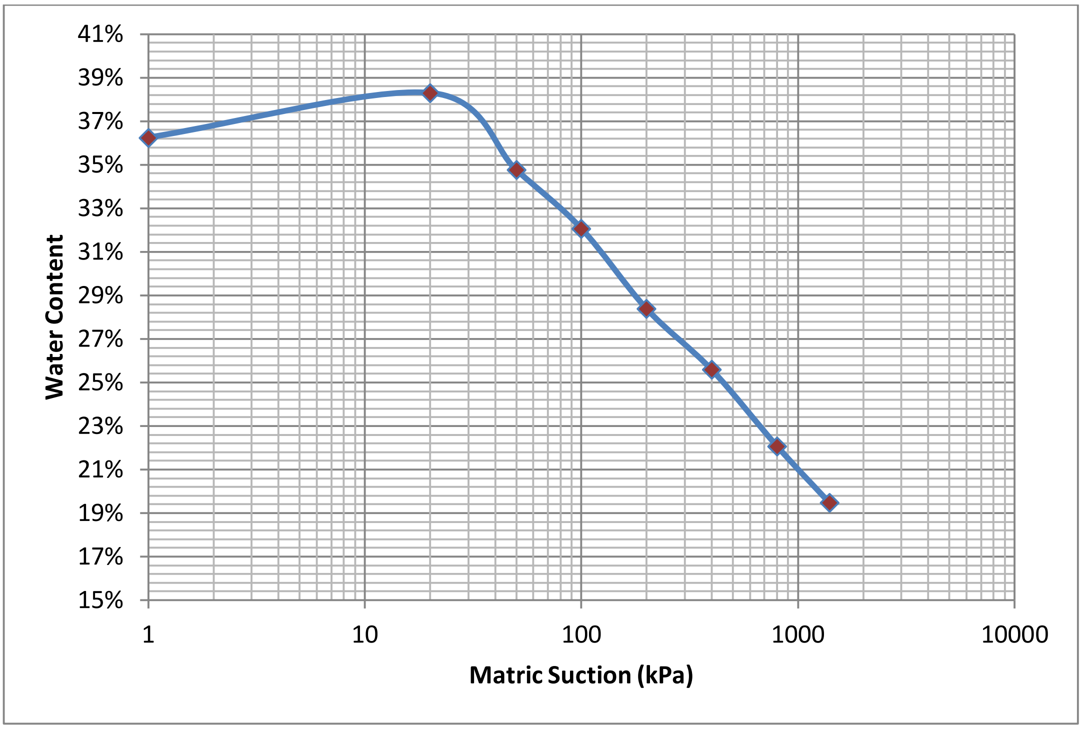


Figure 3.5.1-5 Volumetric water content *versus* soil suction - Stage 1, Sample 2

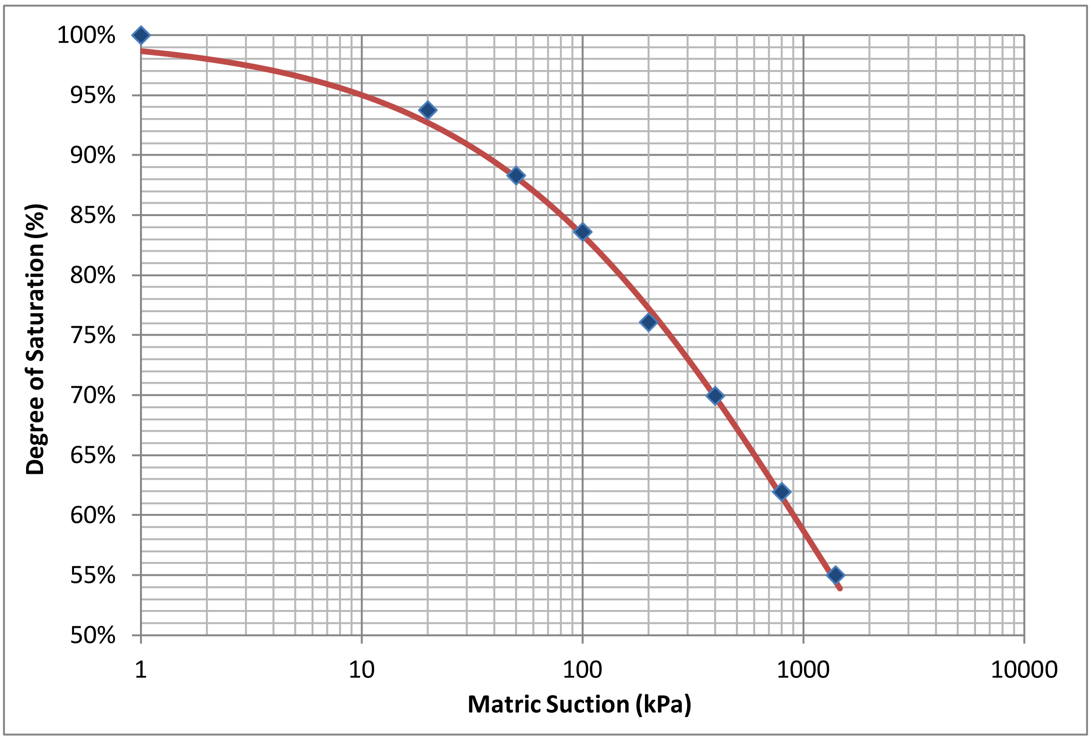


Figure 3.5.1-6 SWCC Test Stage 1, Sample 1- Degree of saturation *versus* soil suction (Van Genuchten equation: a = 600, m = 0.6, n = 0.62)

Sample 3: Silty clay at the Glenroy test site, initial void ratio = 1.14, initial water content = 38.38%. Duration: 06/06/2012 to 27/07/2012

Table 3.5.1-7 Initial condition of SWCC test -stage 1 sample 3

Initial parameters	*Number*
Ring height h	19.93 mm
Ring diameter D_{ring}	50.09 mm
Mass of specimen m_0	68.11g
Initial water content w_i	37.65%
Mass of soil particles m_s	49.48g
Volume of soil particles V_s	18325 mm^3
Mass of water m_w^0	18.63g
Volume of water V_w^0	15633 mm^3
Initial void ratio e_0	1.14

Table 3.5.1-8 Water discharge and calculation of water content -Stage 1, Sample 3

Suction (kPa)	Sample mass after each stage (g) (Ring weight included)	Water discharge (g)	Weight of water, Ww (g)	Water content (%)
1	110.99	0	18.99	**39.98**
20	111.78	-0.79	19.78	**38.38***
50	109.99	1.80	17.98	**36.35**
100	108.36	1.63	16.36	**33.06**
200	106.55	1.81	14.54	**29.39**
400	104.61	1.94	12.61	**25.48**
800	102.94	1.67	10.93	**22.12**
1400	101.60	1.34	9.60	**19.40**

Table 3.5.1-9 Volume change and calculation of void ratio and Degree of saturation- Stage 1, Sample 3

**Water was found absorbed by HAVE ceramic disk*

Suction (kPa)	Vertical deformation (mm)	Disp. volume (mm^3)	Total Volume (mm^3)	$e = (V-V_s)/V_s$ assuming A=Const	S_r (%)
1	0	0	39273.47	**1.14**	**100.00**
20	0.16	315.29	38958.17	**1.13**	**92.03**
50	0.2725	536.98	38421.19	**1.10**	**89.46**
100	0.3575	704.48	37716.71	**1.06**	**84.34**

200	0.22	433.53	37283.19	**1.03**	**76.72**
400	0.25	492.64	36790.54	**1.01**	**68.27**
800	0.22	433.53	36357.02	**0.98**	**60.66**
1400	0.11	216.76	36140.26	**0.97**	**54.89**

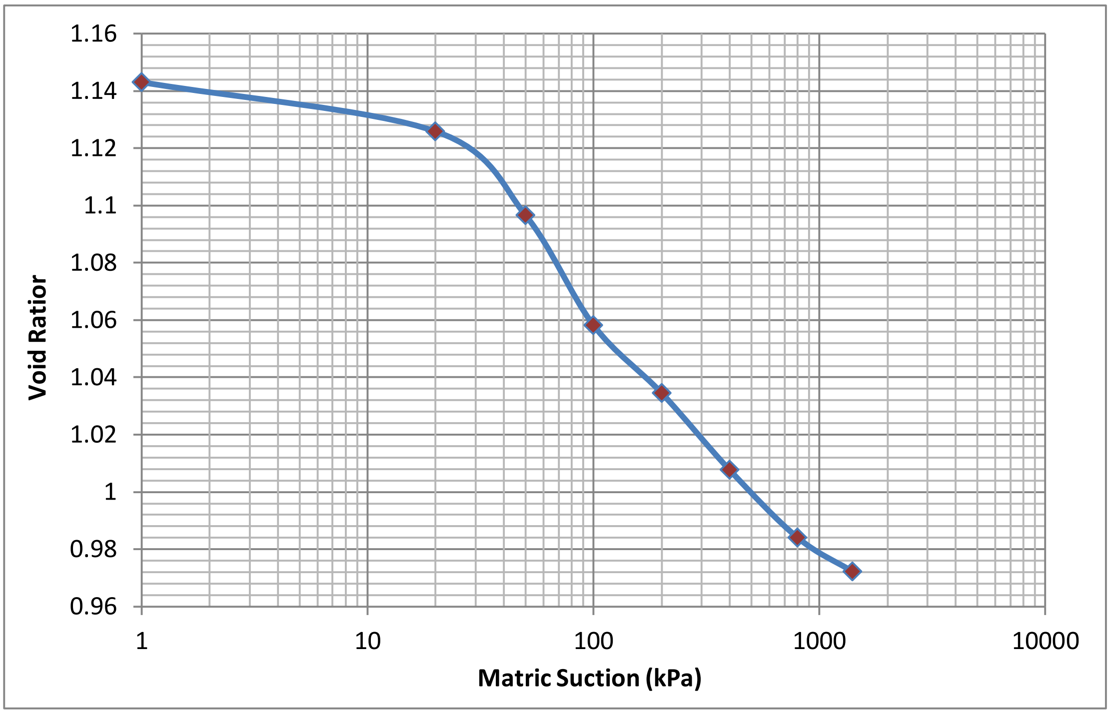


Figure 3.5.1-7 SWCC Test Stage 1, Sample 3 - $e - \ln s$ curve

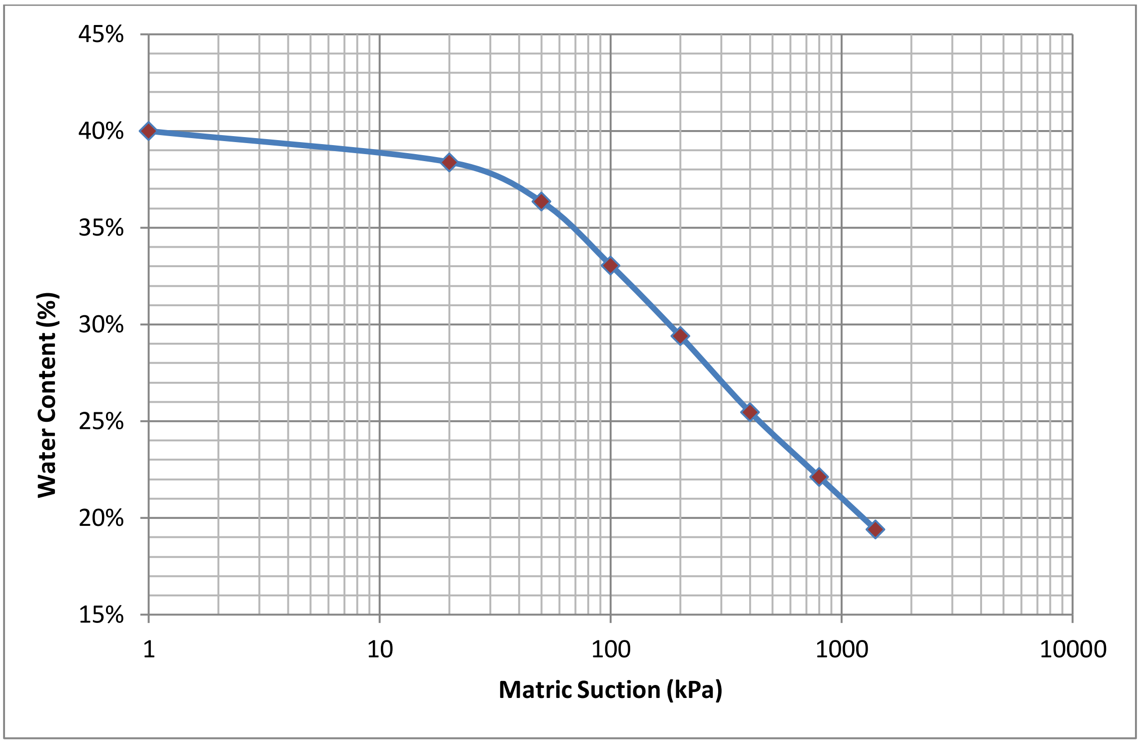


Figure 3.5.1-8 Volumetric water content *versus* soil suction - Stage 1, Sample 3

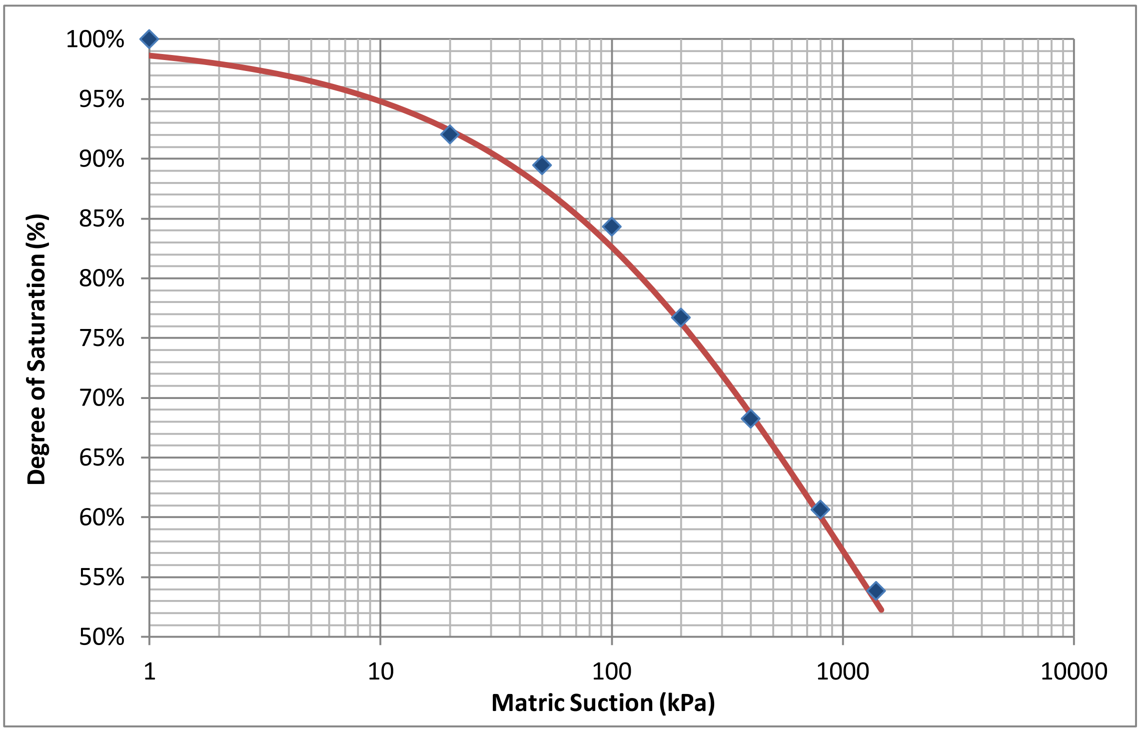


Figure 3.5.1-9 SWCC Test Stage 1, Sample 1- Degree of saturation versus soil suction (Van Genuchten equation: a = 600, m = 0.6, n = 0.65)

3.5.2 *Stage 2 – SWCC test under different initial void ratio*

In stage 2, four SWCC tests were conducted. Four soil samples were initially subjected to a vertical pressures of 200 kPa, 400 kPa, 800 kPa or 1600 kPa respectively to create different initial density.

Sample 1: Silty clay at the Glenroy test site; Duration: 06/09/2012 to 29/10/2012

Table 3.5.2-1 Initial condition of SWCC test -stage 2 sample 1-SP=200 kPa

Initial parameters	*Number*
Ring height h	19.93 mm
Ring diameter D_{ring}	50.09 mm
Mass of specimen m_0	69.28g
Initial water content w_i	35.97%
Mass of soil particles m_s	49.41g
Volume of soil particles V_s	18325 mm^3
Mass of water m_w^0	19.86g
Initial void ratio e_0	0.98

Table 3.5.2-2 Water discharge and calculation of water content -Stage 2, Sample 1

Suction (kPa)	Sample mass after each stage (g) (Ring weight included)	Water discharge (g)	Weight of water, Ww (g)	Water content (%)
1	109.71	0	17.77	**35.97**
20	108.93	0.78	17.00	**34.39**
50	108.29	0.64	16.35	**33.01**
100	107.58	0.71	15.64	**31.66**
200	106.21	1.37	14.27	**28.88**
400	104.29	1.91	12.35	**25.00**
800	102.4102	1.88	10.47	**21.19**
1400	101.60	1.34	9.61	**19.40**

Table 3.5.2-3 Volume change and calculation of void ratio and Degree of saturation- Stage 2, Sample 1

Suction (kPa)	Vertical deformation (mm)	Disp. volume (mm3)	Total Volume (mm3)	$e = (V-V_s)/V_s$ assuming A=Const	S_r (%)
1	0	0	36169.82	**0.98**	**100.00**
20	0.06	108.38	36061.44	**0.97**	**95.70**
50	0.03	49.26	36012.17	**0.97**	**92.33**
100	0.21	413.82	35598.35	**0.95**	**90.44**
200	0.25	492.64	35105.71	**0.92**	**84.92**

400	0.175	344.85	34760.86	**0.90**	**75.07**
800	0.06	108.38	34652.48	**0.88**	**65.04**
1400	0.29	564.90	34087.58	**0.86**	**57.15**

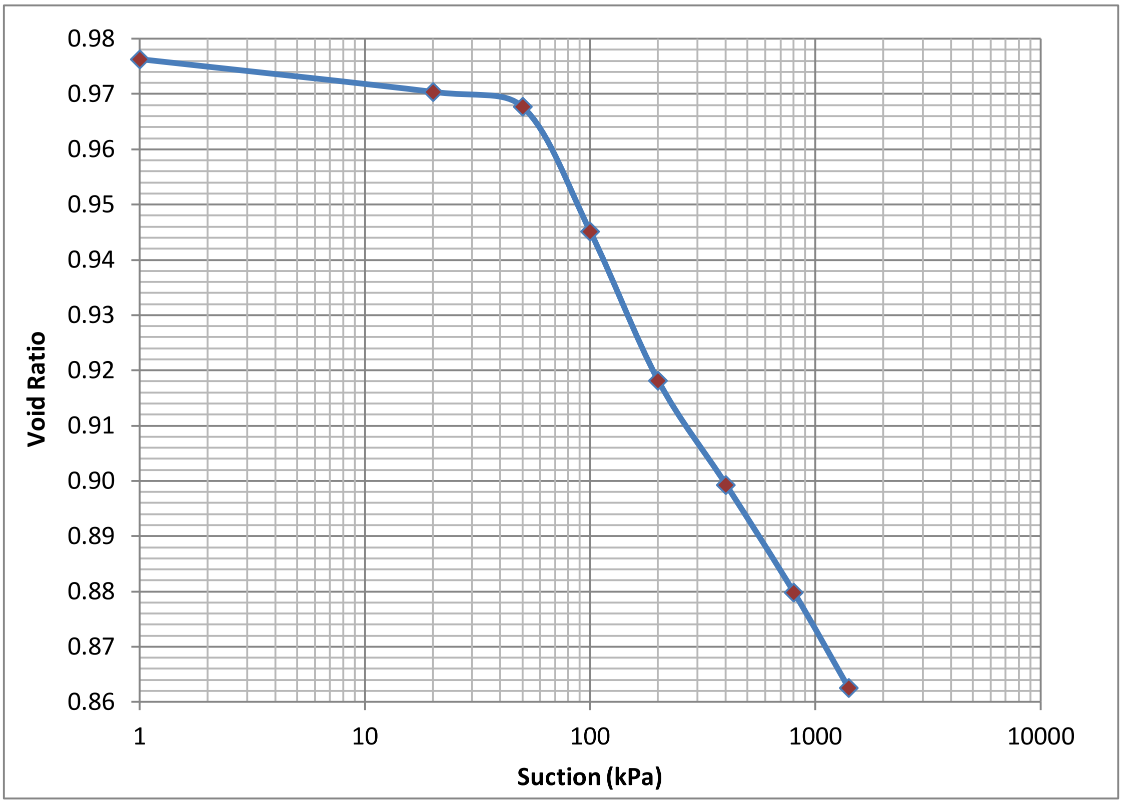


Figure 3.5.2-1 SWCC Test Stage 2, Sample 1 - $e - \ln s$ curve

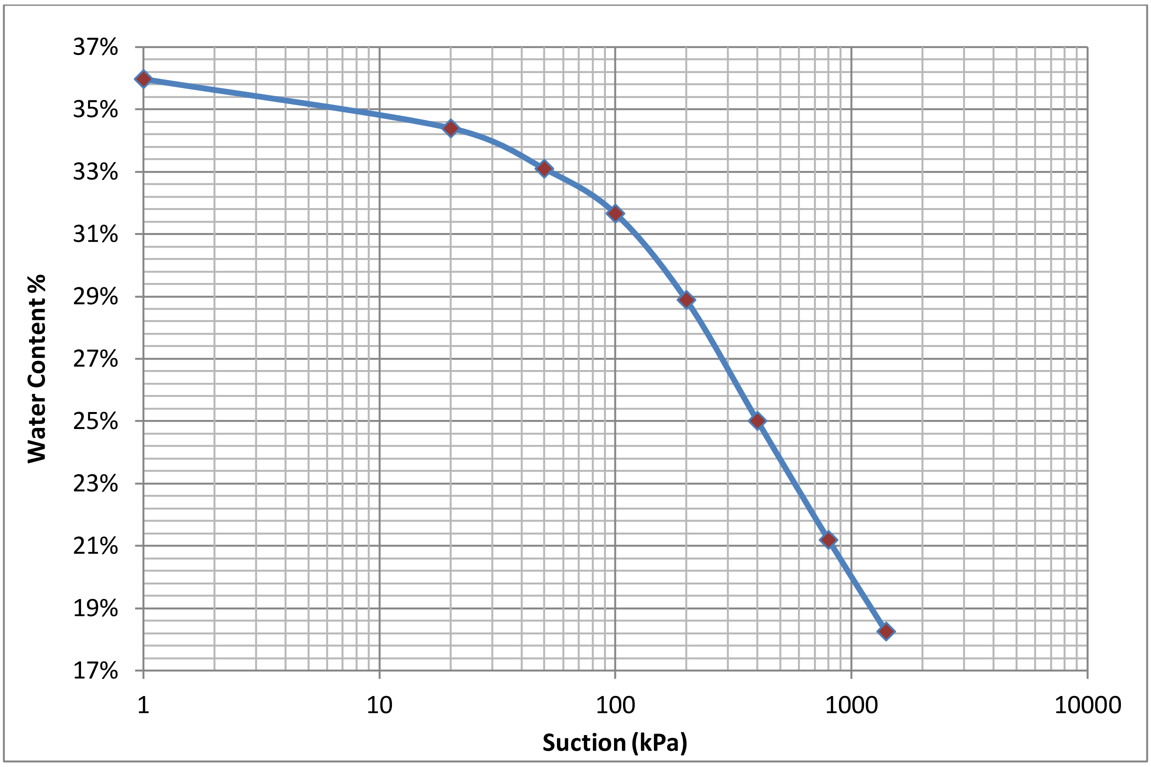


Figure 3.5.2-2 Volumetric water content *versus* soil suction - Stage 2, Sample 1

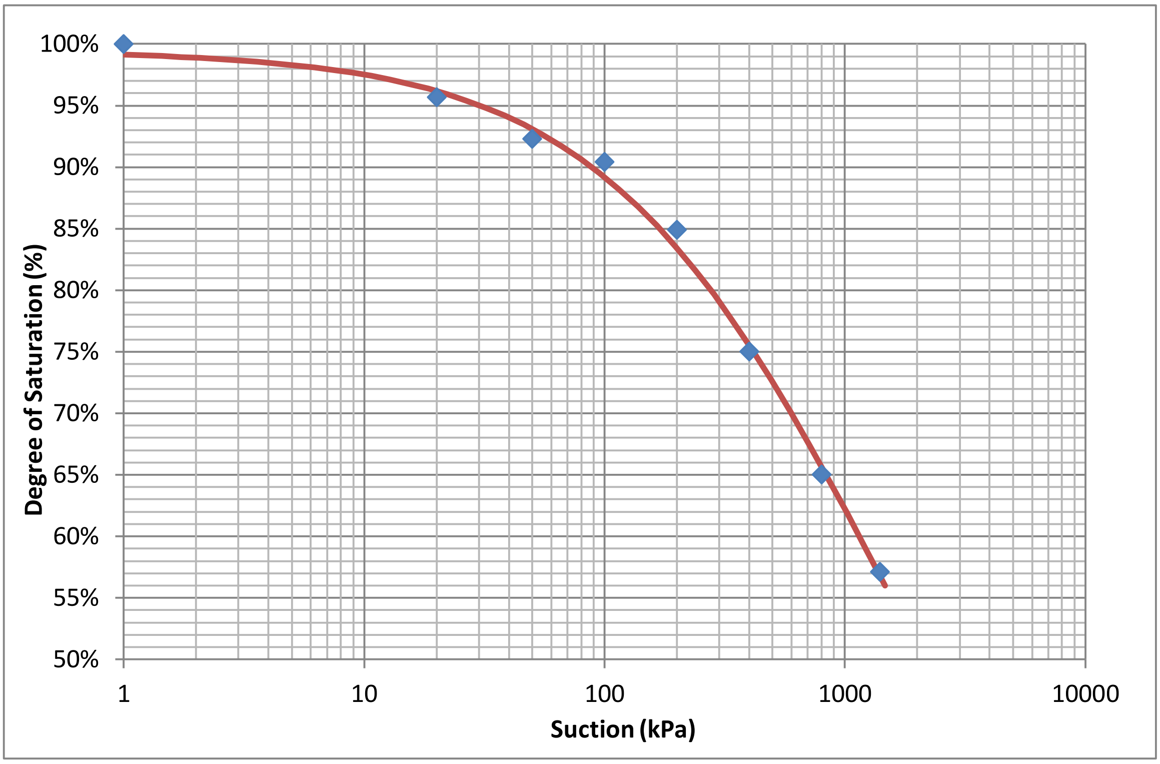


Figure 3.5.2-3 SWCC Test Stage 2, Sample 1- Degree of saturation *versus* soil suction (Van Genuchten equation: a = 800, m = 0.77, n = 0.62)

Sample 2: Silty clay at the Glenroy test site; Duration: 15/11/2012 to 23/01/2013

Table 3.5.2-4 Initial condition of SWCC test -stage 2 sample 2- SP=400 kPa

Initial parameters	*Number*
Ring height h	19.79 mm
Ring diameter D_{ring}	50.21 mm
Mass of specimen m_0	73.26g
Initial water content w_i	33.53%
Mass of soil particles m_s	53.18g
Volume of soil particles V_s	19696 mm^3
Mass of water m_w^0	20.08g
Initial void ratio e_0	0.95

Table 3.5.2-5 Water discharge and calculation of water content -Stage 2, Sample 2

Suction (kPa)	Sample mass after each stage(g) (Ring weight included)	Water discharge (g)	Weight of water, Ww (g)	Water content (%)
1	113.53	0	17.83	**33.53**
20	113.20	0.34	17.49	**32.89**

50	113.03	0.16	17.33	**32.59**
100	112.72	0.32	17.02	**32.00**
200	111.56	1.16	15.86	**29.82**
400	109.74	1.82	14.04	**26.39**
800	107.61	2.13	11.91	**22.38**
1400	106.12	1.49	10.42	**19.59**

Table 3.5.2-6 Volume change and calculation of void ratio and Degree of saturation- Stage 2, Sample 2

Suction (kPa)	Vertical deformation (mm)	Disp. volume (mm^3)	Total Volume (mm^3)	$e = (V-V_s)/V_s$ assuming A=Const	S_r (%)
1	1.21	2385.93	36808.63	**0.95**	**100.00**
20	0.12	231.66	36576.97	**0.94**	**97.42**
50	0.03	59.40	36517.57	**0.93**	**93.83**
100	0.03	49.50	36468.07	**0.91**	**91.25**
200	0.07	138.60	36329.47	**0.90**	**87.14**
400	0.02	1761.62	34567.85	**0.86**	**82.36**
800	0.45	891.01	34970.88	**0.80**	**75.84**

1400	0.09	178.20	34625.71	**0.78**	**67.70**

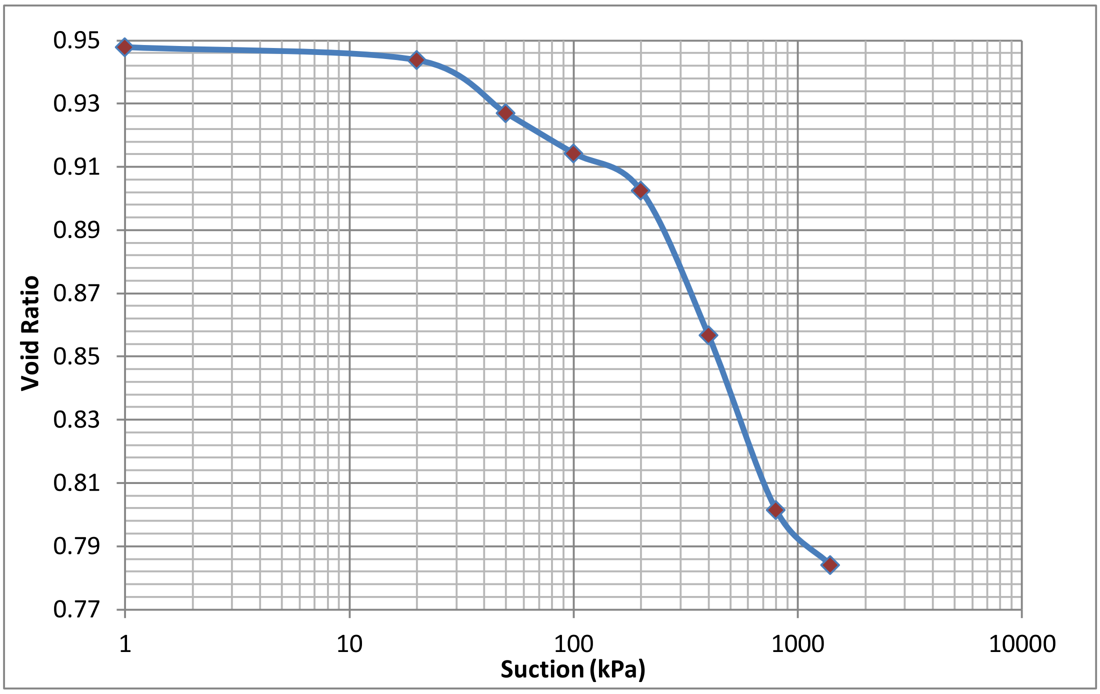


Figure 3.5.2-4 SWCC Test Stage 2, Sample 2 - $e - \ln s$ curve

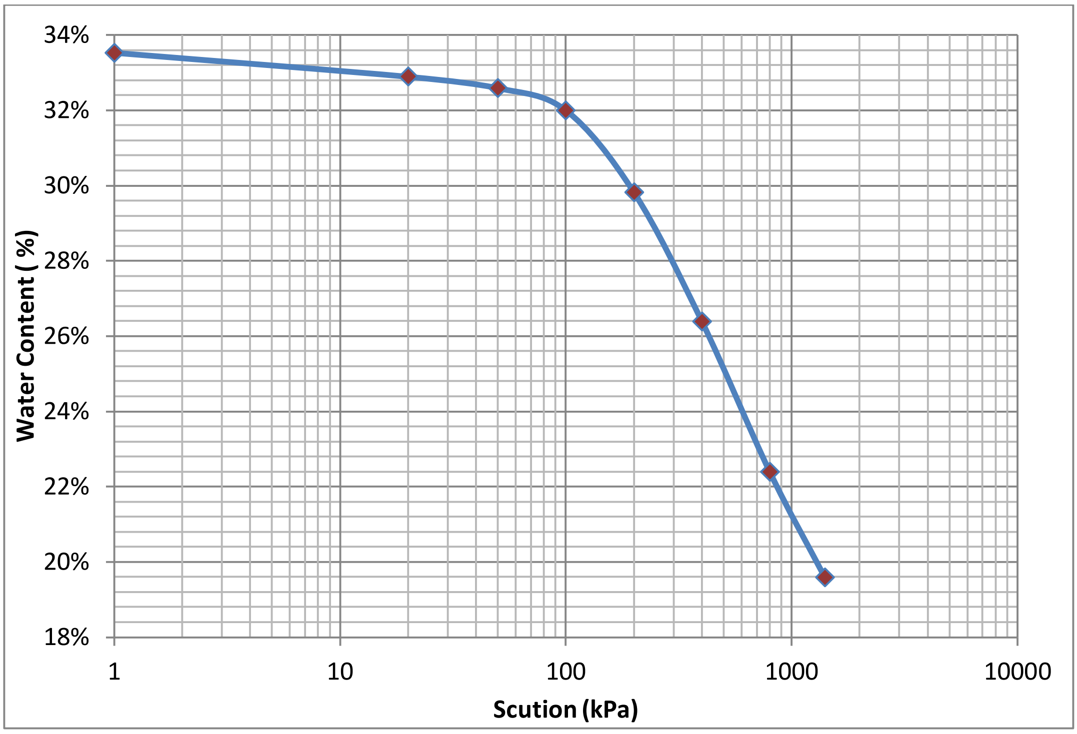


Figure 3.5.2-5 Volumetric water content *versus* soil suction - Stage 2, Sample 2

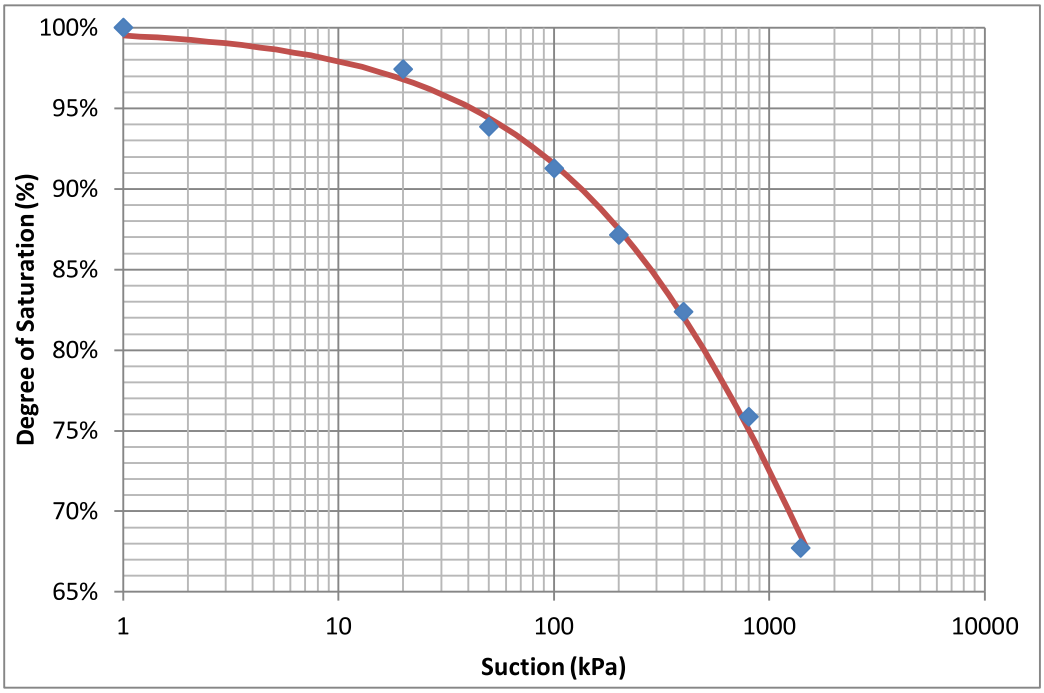


Figure 3.5.2-6 SWCC Test Stage 2, Sample 1- Degree of saturation versus soil suction (Van Genuchten equation: a = 1700, m = 65, n = 0.6)

Sample 3: Silty clay at the Glenroy test site; Duration: 28/11/2012 to 04/02/2013

Table 3.5.2-7 Initial condition of SWCC test -stage 2 sample 3- SP=800 kPa

Initial parameters	*Number*
Ring height h	20.05 mm
Ring diameter D_{ring}	50.22 mm
Mass of specimen m_0	73.17g
Initial water content w_i	30.05%
Mass of soil particles m_s	53.51g
Volume of soil particles V_s	19819 mm^3
Mass of water m_w^0	19.66g
Initial void ratio e_0	0.87

Table 3.5.2-8 Water discharge and calculation of water content -Stage 2, Sample 3

Suction (kPa)	Sample mass after each stage(g) (Ring weight included)	Water discharge (g)	Weight of water, Ww (g)	Water content (%)
1	112.63	0	16.08	**30.05**
20	111.85	0.78	15.30	**28.59**

50	111.42	0.43	14.87	**27.78**
100	110.84	0.58	14.29	**26.69**
200	110.35	0.48	13.80	**25.79**
400	108.85	1.50	12.30	**22.97**
800	108.30	0.55	11.75	**21.97**
1400	107.03	1.27	10.48	**19.59**

Table 3.5.2-9 Volume change and calculation of void ratio and Degree of saturation- Stage 2, Sample 3

Suction (kPa)	Vertical deformation (mm)	Disp. volume (mm^3)	Total Volume (mm^3)	$e = (V-V_s)/V_s$ assuming A=Const	S_r (%)
1	1.205	2385.93	36808.63	**0.87**	**100.00**
20	0.117	231.66	36576.97	**0.86**	**99.56**
50	0.03	59.40	36517.57	**0.856**	**98.07**
100	0.025	49.50	36468.07	**0.852**	**95.99**
200	0.07	138.60	36329.47	**0.84**	**92.71**
400	0.02	1761.62	34567.85	**0.80**	**86.36**
800	0.45	891.01	34970.88	**0.76**	**82.82**
1400	0.09	178.20	34625.71	**0.74**	**75.03**

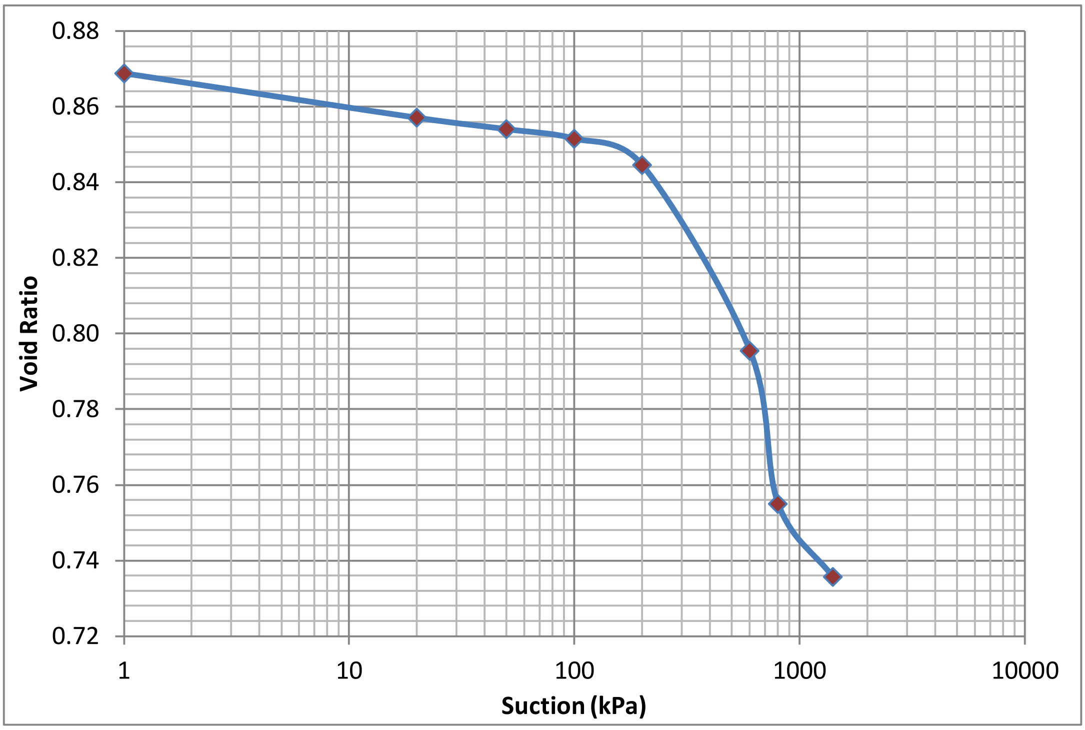


Figure 3.5.2-7 SWCC Test Stage 2, Sample 3 - $e - \ln s$ curve

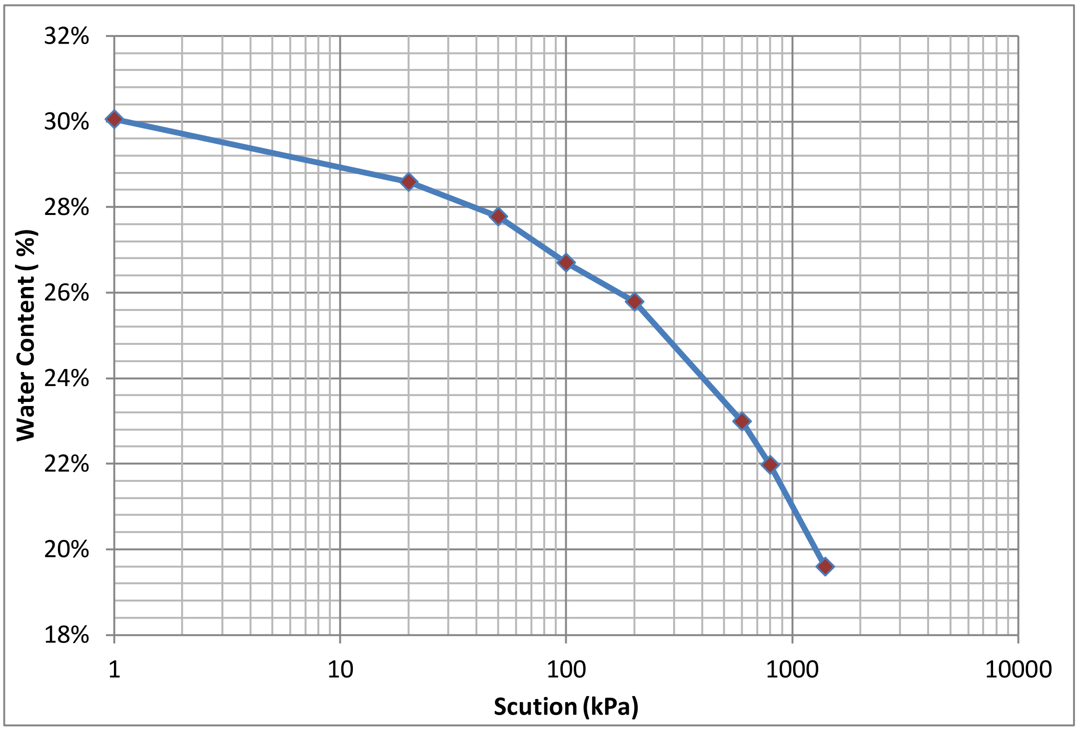


Figure 3.5.2-8 Volumetric water content versus soil suction - Stage 2, Sample 3

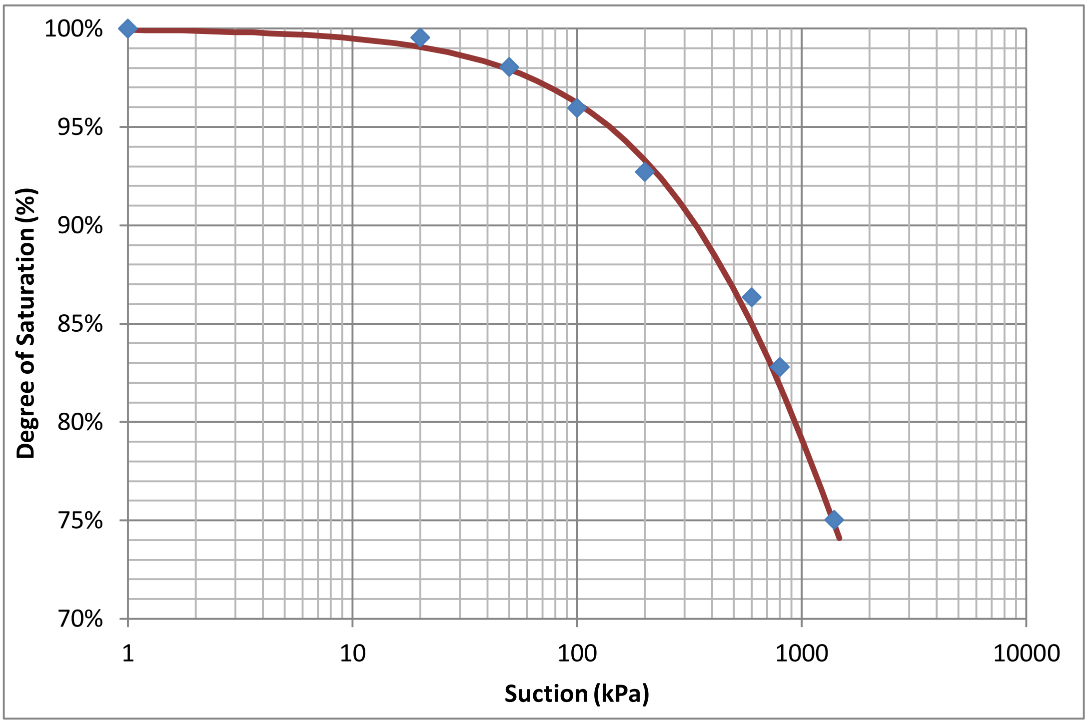


Figure 3.5.2-9 SWCC Test Stage 2, Sample 1- Degree of saturation versus soil suction (Van Genuchten equation: a = 1200, m = 0.9, n = 0.38)

Sample 4: Silty clay at the Glenroy test site; Duration: 12/02/2013 to 04/04/2013

Table 3.5.2-10 Initial condition of SWCC test -stage 2 sample 4 – SP=1600 kPa

Initial parameters	*Number*
Ring height h	19.72 mm
Ring diameter D_{ring}	50.18 mm
Mass of specimen m_0	68.9729g
Initial water content w_i	38.908%

Mass of soil particles m_s	49.65g
Volume of soil particles V_s	18390 mm^3
Mass of water m_w^0	19.32g
Initial void ratio e_0	0.78

Table 3.5.2-11Water discharge and calculation of water content -Stage 2, Sample 4

Suction (kPa)	Sample mass after each stage (Ring weight included)	Water discharge	Weight of water, Ww (g)	Water content (%)
1	112.63	0	16.08	**40.03**
20	111.85	0.78	15.30	**40.07**
50	111.42	0.43	14.87	**39.84**
100	110.84	0.58	14.29	**39.33**
200	110.35	0.48	13.80	**38.48**
400	108.85	1.50	12.30	**36.92**
800	108.30	0.55	11.75	**34.15**
1400	107.03	1.27	10.48	**31.35**

Table 3.5.2-12 Volume change and calculation of void ratio and Degree of saturation- Stage 2, Sample 4

Suction (kPa)	Vertical deformation (mm)	Disp. volume (mm3)	Total Volume (mm3)	$e = (V-V_s)/V_s$ assuming A=Const	S_r (%)
1	1.205	2385.93	36808.63	**0.78**	**100.00**
20	0.117	231.66	36576.97	**0.75**	**99.10**
50	0.03	59.40	36517.57	**0.74**	**97.69**
100	0.025	49.501	36468.07	**0.73**	**96.59**
200	0.07	138.60	36329.47	**0.71**	**94.63**
400	0.02	1761.62	34567.85	**0.69**	**92.57**
800	0.45	891.01	34970.88	**0.67**	**89.04**
1400	0.09	178.20	34625.71	**0.65**	**85.85**

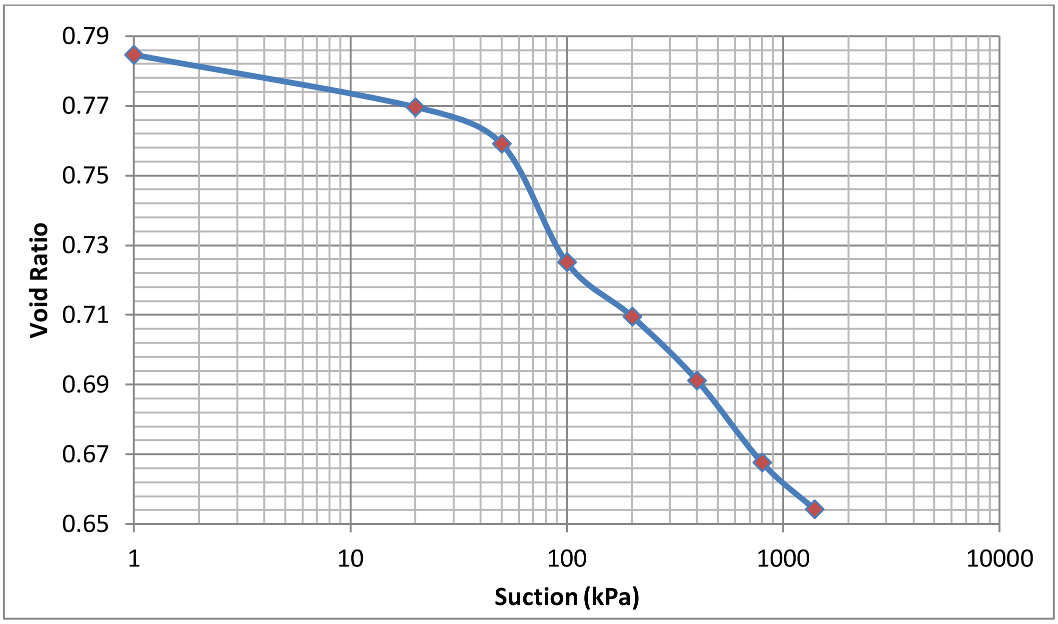


Figure 3.5.2-10 Volumetric water content versus soil suction - Stage 2, Sample 4

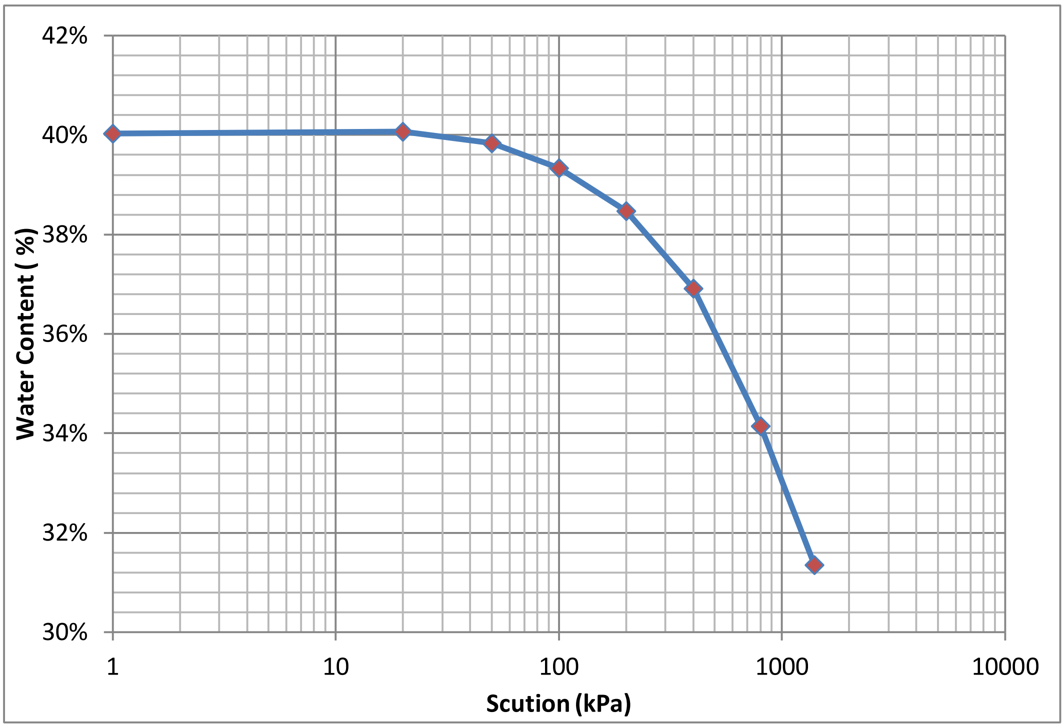


Figure 3.5.2-11 Volumetric water content versus soil suction - Stage 2, Sample 4

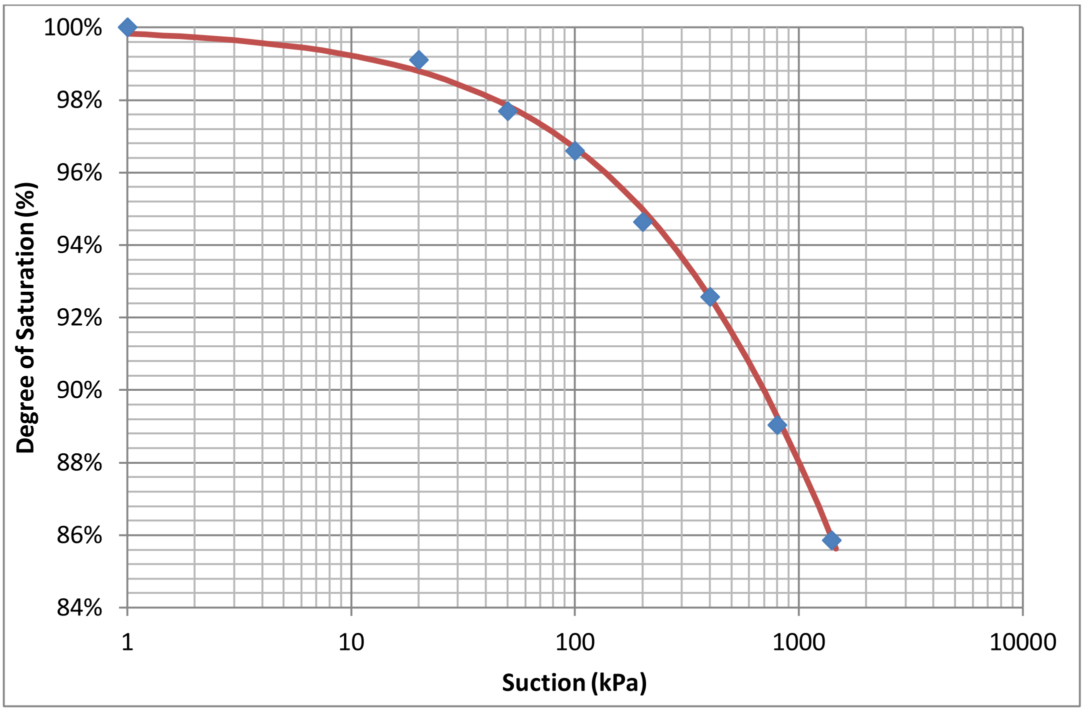


Figure 3.5.2-12 SWCC Test Stage 2, Sample 1- Degree of saturation versus soil suction (Van Genuchten equation: a = 2000, m = 0.66, n = 0.26)

3.5.3 Stage 3 – SWCC test under different temperatures

In stage 3, one non-isothermal SWCC test was conducted. The test was carried out at 60°C. All initial parameters were estimated under reference/ room temperature of 25°C.

Sample 1: Silty clay at the Glenroy test site; Duration: 06/09/2012 to 12/10/2012.

Table 3.5.3-1 Initial condition of SWCC test -Stage 3, Sample 1

Initial parameters	*Number*
Ring height h	20.09 mm

Ring diameter D_{ring}	50.16 mm
Mass of specimen m_0	70.58g
Initial water content w_i	42.17%
Mass of soil particles m_s	50.57g
Volume of soil particles V_s	18.73 mm^3
Mass of water m_w^0	20.01g
Initial void ratio e_0	1.12

Table 3.5.3-2 Water discharge and calculation of water content -Stage 3, Sample 1

Suction (kPa)	Sample mass after each stage(g) (Ring weight included)	Water discharge (g)	Weight of water, Ww (g)	Water content (%)
1	114.25	0	21.33	**42.17**
20	113.43	0.82	20.51	**40.55**
50	110.58	2.85	17.66	**36.92**
100	106.39	4.19	13.47	**26.65**
200	99.38	7.02	6.45	**20.38**
400	97.46	1.92	4.53	**15.65**

800	97.25	0.21	4.32	**9.68**
1400	97.35	-0.096	4.42	**8.74**

Table 3.5.3-3Volume change and calculation of void ratio and Degree of saturation- Stage 3, Sample 1

Suction (kPa)	Vertical deformation (mm)	Disp. volume (mm3)	Total Volume (mm3)	e = (V-V_s)/V_s assuming A=Const	S_r (%)
1	1.205	2385.93	36808.63	**1.107**	**100.00**
20	0.117	231.66	36576.97	**1.09**	**87.53**
50	0.03	59.40	36517.57	**1.04**	**78.09**
100	0.025	49.50	36468.07	**0.98**	**69.88**
200	0.07	138.60	36329.47	**0.92**	**56.71**
400	0.02	1761.62	34970.88	**0.87**	**46.58**
800	0.45	891.01	34625.71	**0.83**	**28.95**
1400	0.09	178.20	34567.84	**0.82**	**25.29**

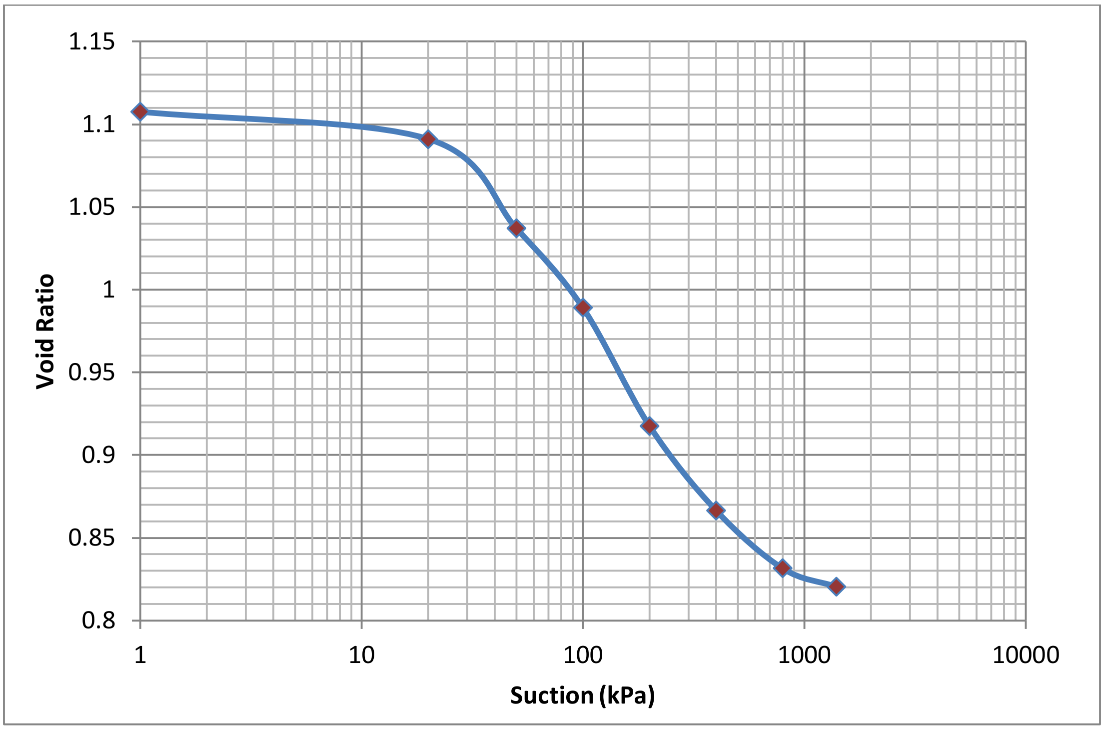


Figure 3.5.3-1 SWCC Test Stage 3, Sample 1 - $e - \ln s$ curve

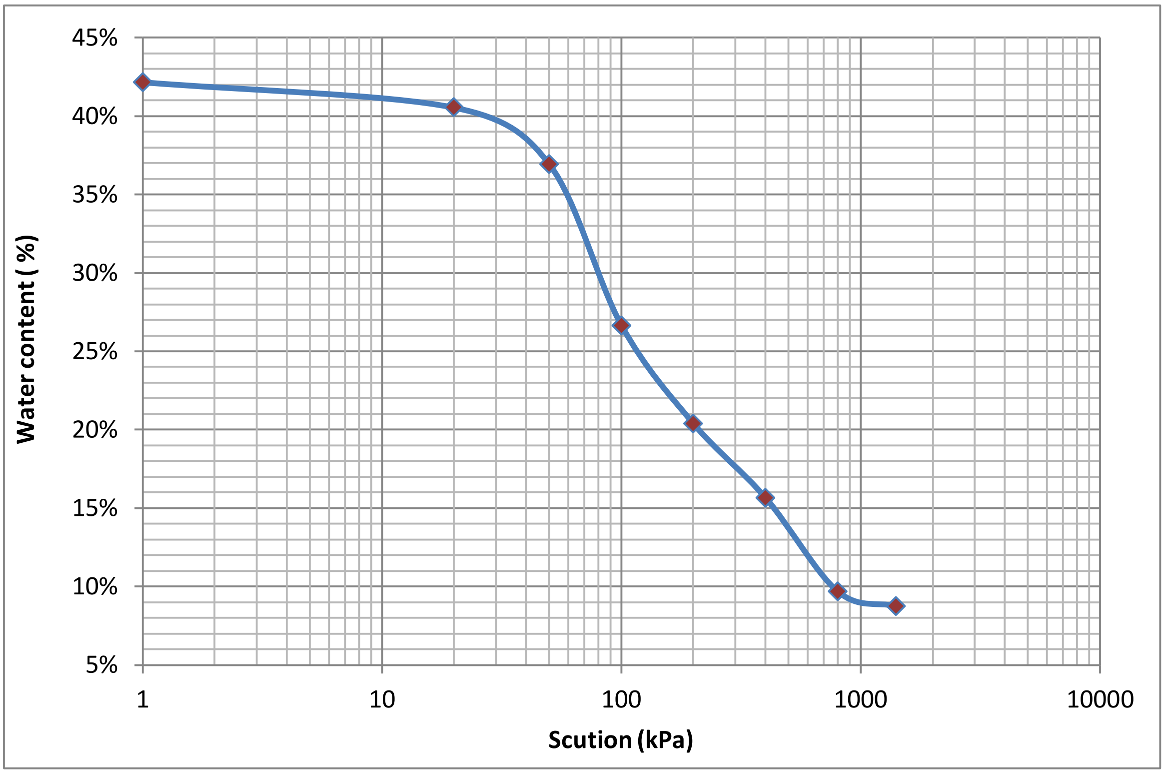


Figure 3.5.3-2 Volumetric water content versus soil suction - Stage 3, Sample 1

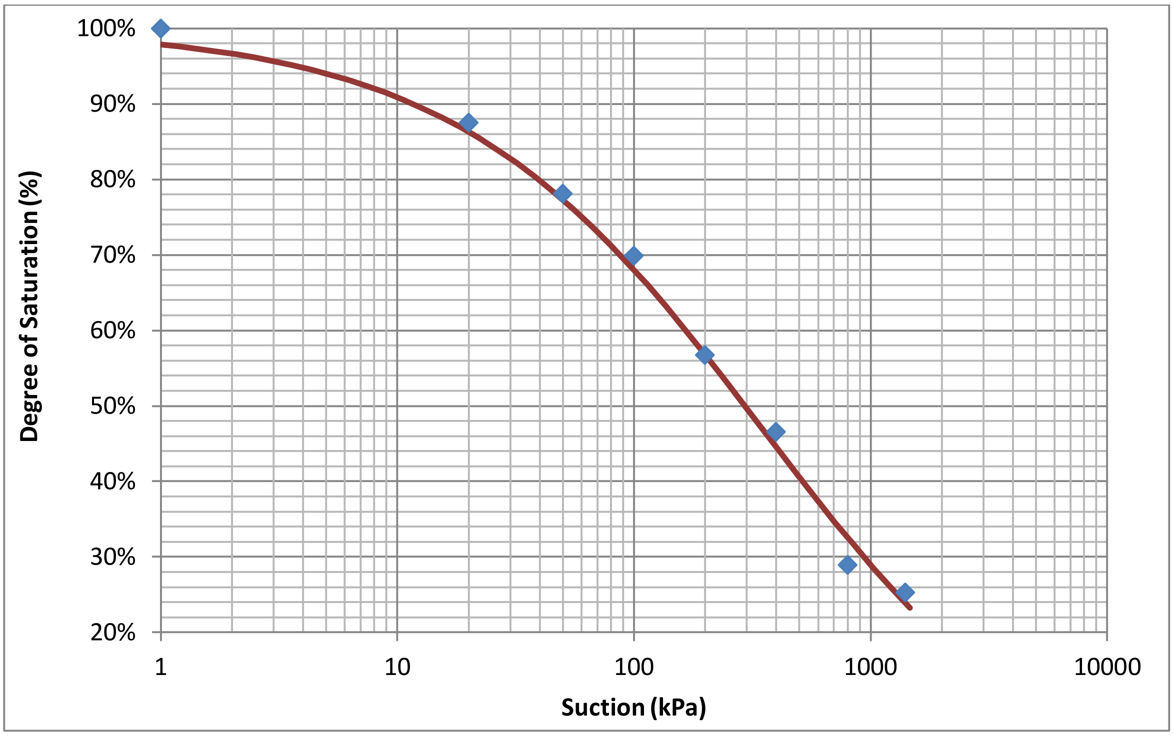


Figure 3.5.3-3 SWCC Test Stage 2, Sample 1- Degree of saturation versus soil suction (Van Genuchten equation: a = 650, m = 0.65, n = 1.42)

3.6 *Data analysis and comparison*

3.6.1 Stage 1 – SWCC test under constant temperature and same initial void ratio

Table 3.6.1-1 summarises the data corresponding to conversional SWCC tests under constant temperature. The initial void ratio for the second and third test is very similar (1.14 and 1.13), and the test results are corresponding to each other. The first test was for device calibration and the sample was prepared in a different time with a smaller initial consolidation pressure (less than 55kPa). Therefore, the initial void ratio is less (0.79) as well as the test result does not correspond to the second and third tests. Figure 3.6.1-1 shows the *e*-ln *s* curve plotted based on table 3.6.1-1.

Table 3.6.1-2 summarise the results of degree of saturation for stage 1. Figure 3.6.1-2 shows the *degree of saturation* -ln *s* curve plotted based on table 3.6.1-2. Van Genuchten SWCC equation was used for the fitting equation. The result can be summarised as below:

- Fitting parameter for test 1 (28/01/2012) equal to: a=400, m=0.7 and n=0.66.

- Fitting parameter for test 2 (06/06/2012#1) equal to: a=600, m=0.6 and n=0.65.
- Fitting parameter for test 3 (06/06/2012#2) equal to: a=600, m=0.6 and n=0.62.
- The sample with a low initial void ratio will result in a relatively low degree of saturation at the end of the test.
- With an increasing suction value, the influence on the void ratio and the water retention capacity is smooth between each stage.

Table 3.6.1-1Void ratio results for SWCC Test- Stage 1

Suction (kPa)	**e**		
	28/01/2012	06/06/2012 #1	06/06/2012 #2
1	0.79	1.14	1.13
20	0.77	1.13	1.10
50	0.76	1.10	1.06
100	0.74	1.06	1.04
200	0.72	1.03	1.01
400	0.70	1.01	0.99
800	0.69	0.98	0.96
1400	0.68	0.97	0.96

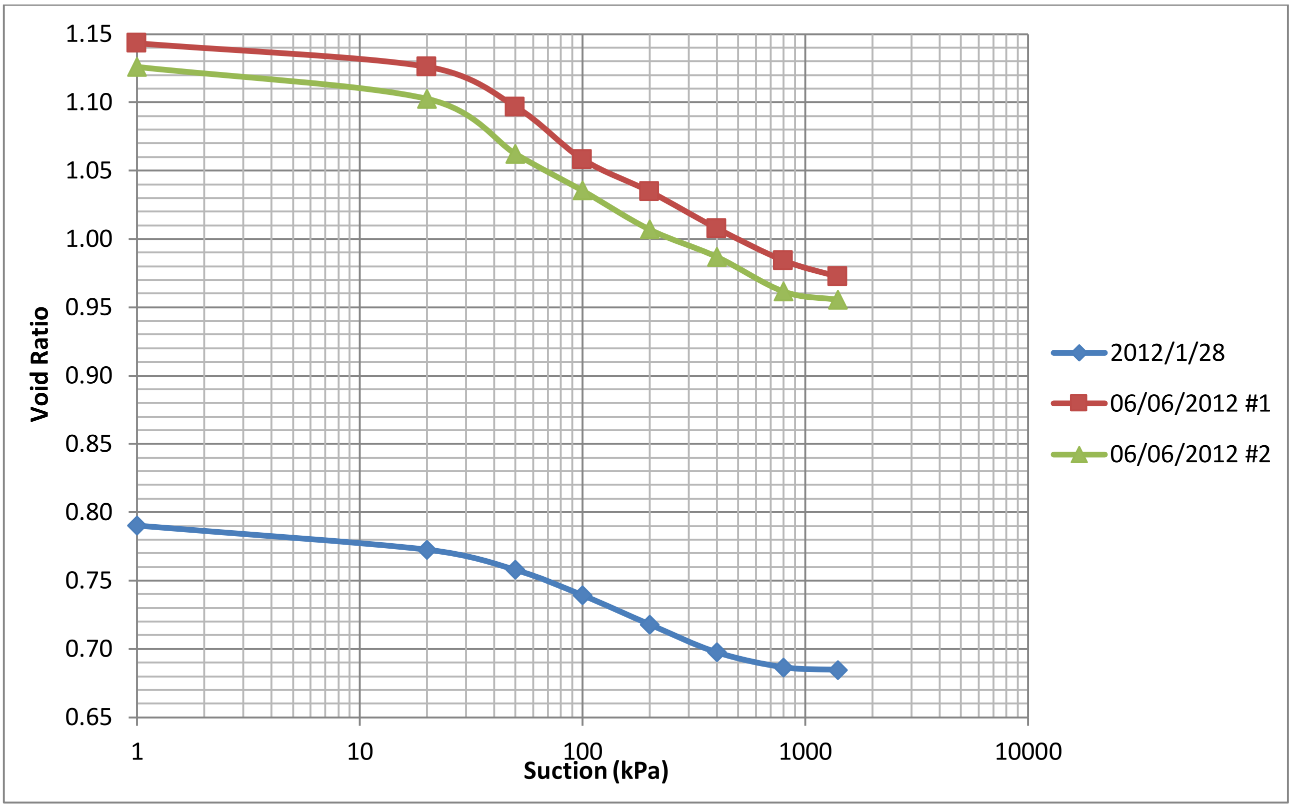


Figure 3.6.1-1 $e - \ln s$ curve for SWCC Test- Stage 1

Table 3.6.1-2 Degree of Saturation results for SWCC Test- Stage 1

Suction (kPa)	**Sr (%)**		
	2012/1/28	06/06/2012 #1	06/06/2012 #2
1	100.00	100.00	100.00%
20	92.64	92.03	93.75%
50	87.33	89.49	88.32%
100	80.32	84.34	83.60%
200	71.88	76.71	76.08%
400	59.25	68.27	69.96%
800	56.83	60.66	61.97%
1400		54.89	54.99%

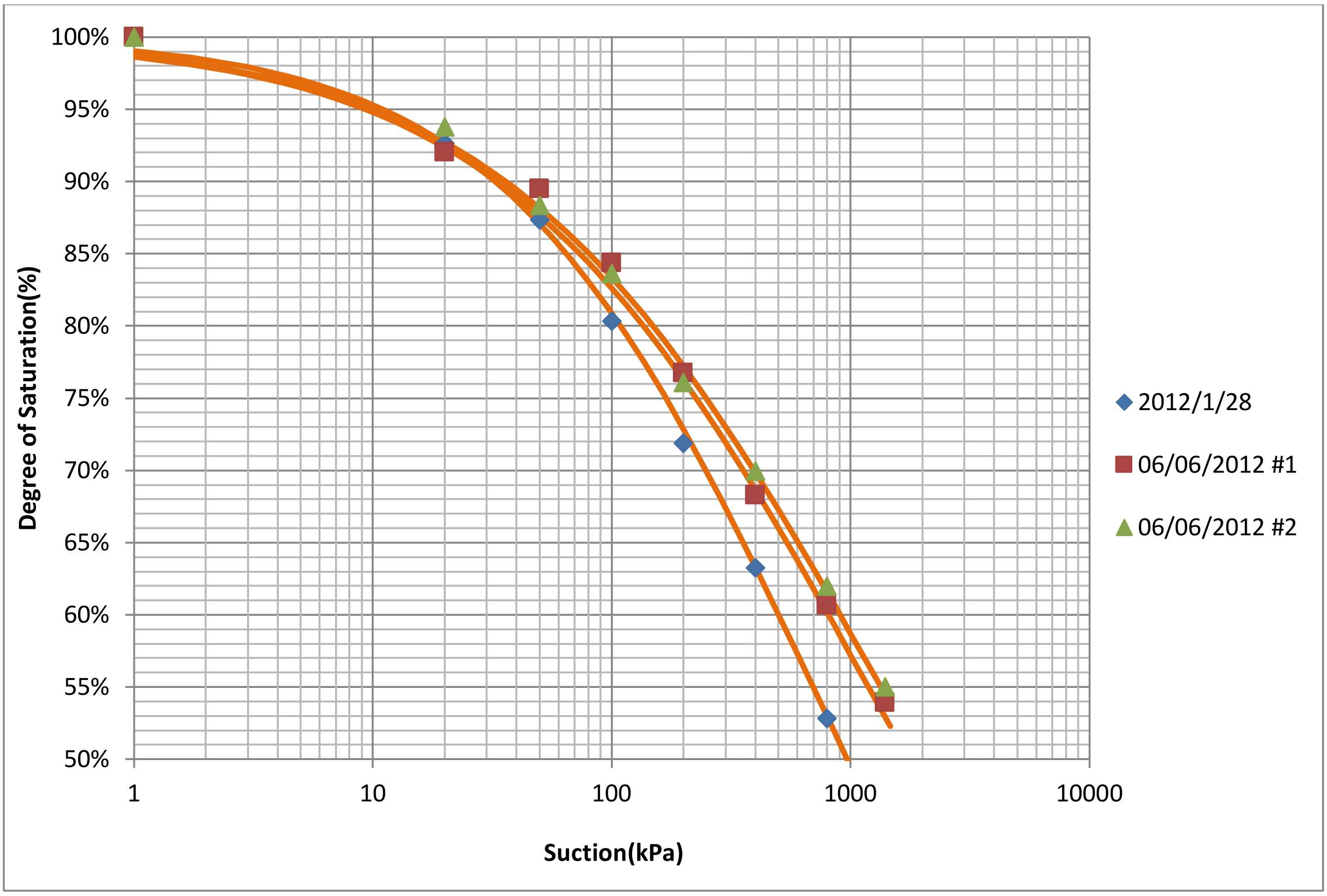


Figure 3.6.1-2 Degree of saturation versus soil suction for SWCC test - Stage 1

3.6.2 Stage 2 – SWCC test under different initial void ratio

Table 3.6.2-1 summarises the data corresponding to SWCC tests under different initial void ratio. Four soil samples prepared at the same time (reconstitution process) under same initial conditions (same consolidation pressure, same initial void ratio) were artificially subjected to four different pre-consolidation pressures: 200kPa, 400kPa, 800kPa and 1600kPa to create different initial void ratio as shown in table 3.5.2-1.

Table 3.6.2-2 summarise the results of degree of saturation for stage 2. Figure 3.6.1-2 shows the *degree of saturation* -ln *s* curve plotted based on table 3.6.2-2. Van Genuchten SWCC equation was used for the fitting equation. The result can be summarised as below:

- Fitting parameter for test 1 (200kPa) equal to: a=850, m=0.77 and n=0.62.
- Fitting parameter for test 2 (400kPa) equal to: a=1700, m=0.65 and n=0.6.
- Fitting parameter for test 3 (800kPa) equal to: a=1500, m=0.88 and n=0.43.
- Fitting parameter for test 4 (1600kPa) equal to: a=2000, m=0.66 and n=0.26.
- A decrease of the void ratio leads to an increase of the degree of saturation. In other words, when suction is constant, the water retention capacity increases corresponding to decreases of void ratio. Also, it is a linear relationship.
- The sample with a high initial void ratio tends to have a low water retention capacity after 100kPa (Air entry value).
- By observation, the volume change of the sample become less significant when the pre-consolidation pressure increases.

Table 3.6.2-1 Void ratio results for SWCC Test- Stage 2

Suction (kPa)	**e**			
	200kPa	400kPa	800kPa	1600kPa
1	0.98	0.95	0.87	0.78
20	0.97	0.94	0.86	0.77
50	0.97	0.93	0.85	0.76
100	0.95	0.91	0.846	0.73
200	0.92	0.90	0.84	0.71
400	0.90	0.86	0.80	0.69
800	0.88	0.80	0.76	0.67
1400	0.86	0.78	0.74	0.65

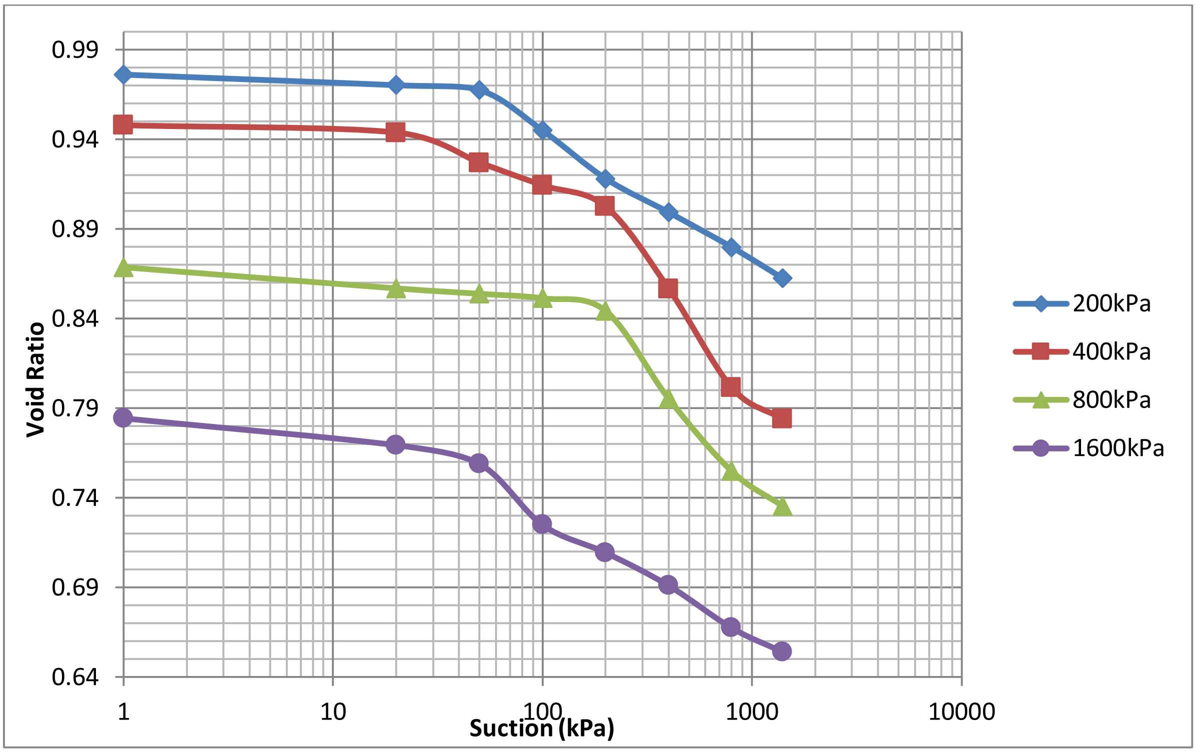


Figure 3.6.2-1 $e - \ln s$ curve for SWCC Test- Stage 2

Table 3.6.2-2 Degree of Saturation results for SWCC Test- Stage 2

Suction (kPa)	**Sr (%)**			
	200kPa	400kPa	800kPa	1600kPa
1	100.00%	100.00%	100.00%	100.00%
20	95.70%	97.42%	99.56%	99.10%
50	92.33%	93.83%	98.07%	97.69%
100	90.44%	91.25%	95.99%	96.59%
200	84.92%	87.14%	92.71%	94.63%
400	75.07%	82.36%	86.36%	92.57%
800	65.04%	75.84%	82.82%	89.04%
1400	57.15%	67.70%	75.03%	85.85%

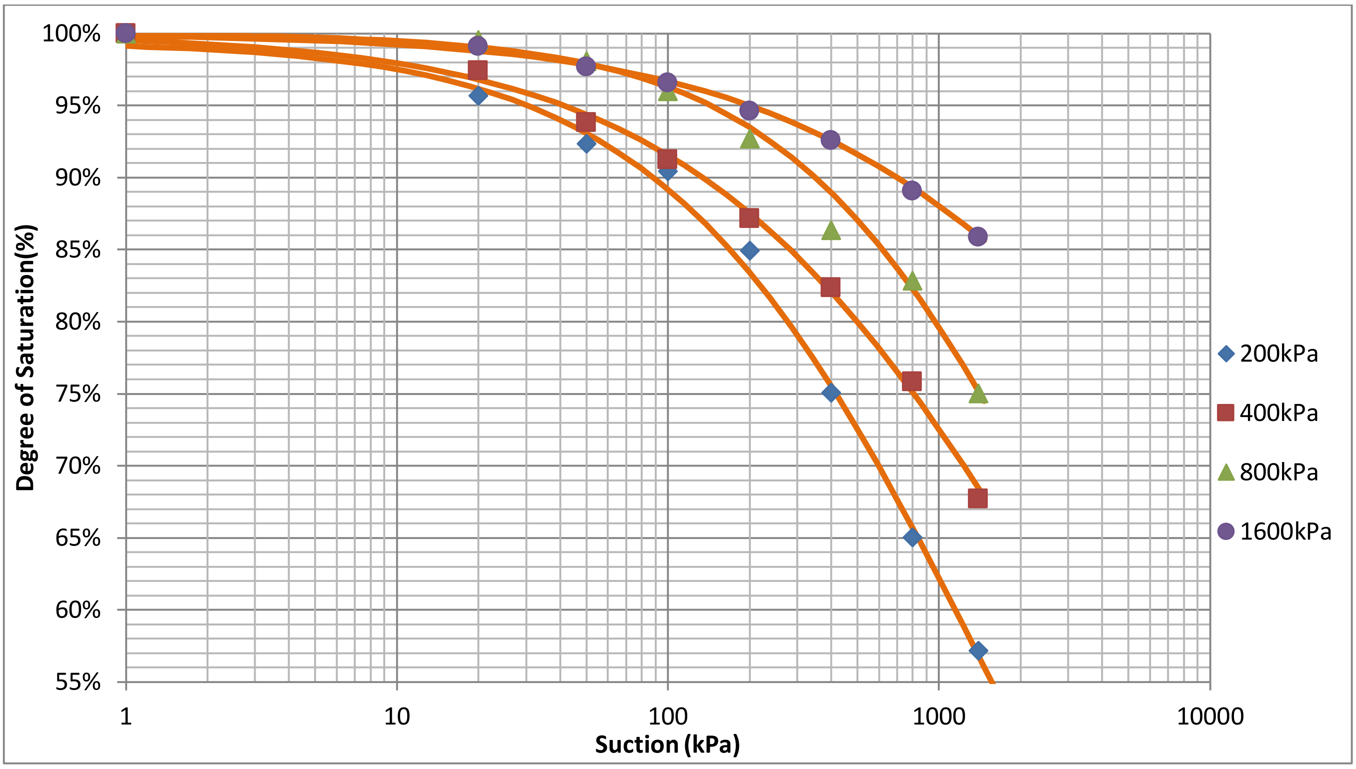


Figure 3.6.2-2 Degree of saturation versus soil suction for SWCC test - Stage 2

3.6.3 Stage 3 – SWCC test under different temperature

Table 3.6.3-1 summarise the resultsobtained from the SWCC test. The test was conducted under 60 ºC. Figure 3.6.3-2 shows the *degree of saturation* -ln *s* curve plotted based on table 3.6.3-1. Van Genuchten SWCC equation was used for the fitting equation. The result can be summarised as below:

- Fitting parameter for test 1 (60ºC) equal to: a=600, m=0.65 and n=1.42.
- It can be seen that the degree of saturation has been influenced by temperature significantly, especially at low suction stage (20kPa to 400kPa). At high suction (> 800 kPa), the influence of the temperature on water retention capacity is less significant. In other words, the water retention capacity decreases with increases of temperature at low suction stage. The influence becomes less significant at high suction.

Table 3.6.3-1 Result table for stage 3

Suction	e	Sr
1	1.11	100.00%
20	1.09	87.54%
50	1.04	78.10%
100	0.99	69.88%
200	0.92	56.72%
400	0.87	46.58%
800	0.83	28.95%
1400	0.82	25.29%

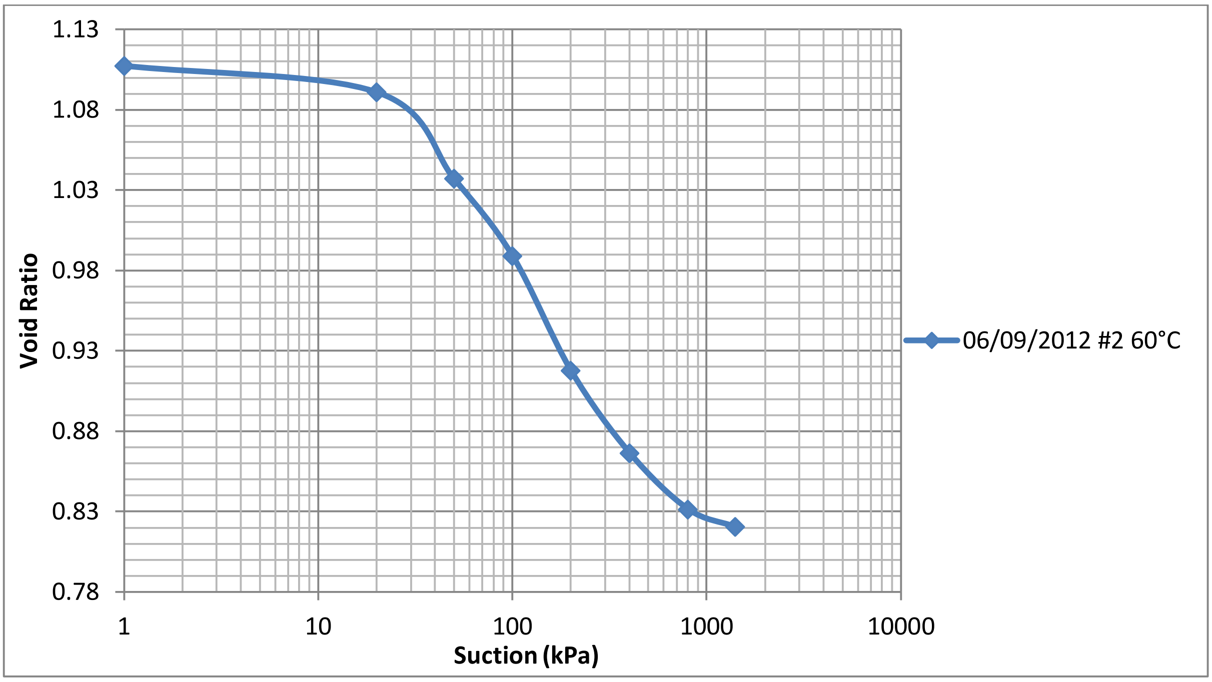


Figure 3.6.3-1 $e - \ln s$ curve for SWCC Test- Stage 3

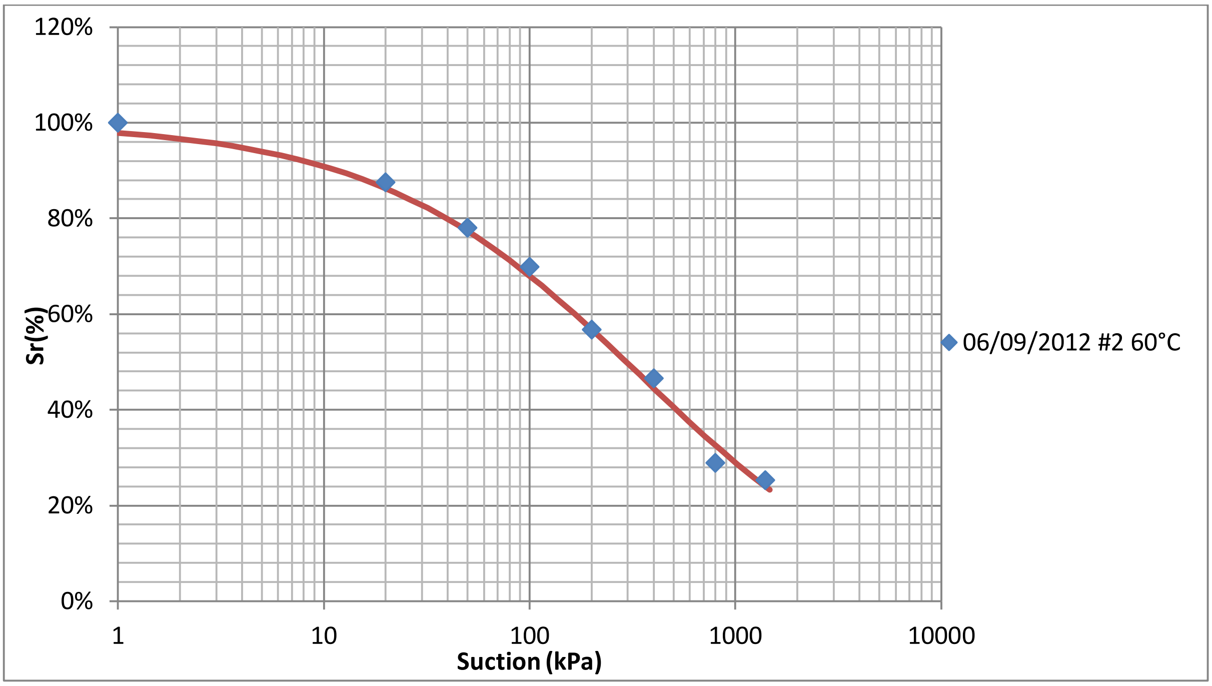


Figure 3.6.3-2 Degree of saturation versus soil suction for SWCC test - Stage 2

Chapter 4 CONCLUSIONS

4.1 Conclusions

In this thesis, the hydraulic behaviour of unsaturated soil has been studied. The experimental work was undertaken during the study duration. Three different sets of SWCC testing were performed with soil samples subjected to different initial conditions.

In stage 1, three conventional SWCC tests were performed on soil specimens under the same initial testing conditions. The aims of conducting this set of tests are, firstly for machine calibration. As it was a new set of equipment and it was necessary to do so for prevention of machine setting errors. Secondly to test the sample itself, get an original base line, known the basic soil properties and also for comparison purpose. For the second and third test, I was aiming to set a benchmark for the later on tests, and also for a more accurate comparison. Before testing, special attention were paid to the water content of soil specimens, it was carefully monitored as it is one of the most important soil properties, one of the key factor in this research. Also for the volume changes of the specimen, it was carefully measured, because the volume change of the sample is reflecting to the change of void ratio and related to the degree of saturation.

In stage 2, three SWCC tests were conducted on the soil specimens with different initial void ratios. The detailed result and analysis can be found in Chapter 3 (?). The main results and conclusions drawn in this study can be summarised as below:

First of all, the sample with a low initial void ratio will result in a relatively low degree of saturation at the end of the test. It is can be understood as the larger void in a soil specimen is decreasing soil's water retention ability. When under same suction or constant suction, a soil with a low initial void ratio would lose more moisture than the soil with a higher initial void ratio.

Secondly, a decrease of the void ratio leads to an increase of the degree of saturation. In other words, when suction is constant, the degree of saturation increases corresponding to a decreases of void ratio. Also, the relationship between them is linear.

Thirdly, the sample with a high initial void ratio tends to have a low water retention capacity after 100 kPa (Air entry value). As can be seen from Figure 3.6.2-1, when air starts to enter the test sample, the sample with a higher initial void ratio has a relatively shaper drop compare with the sample with a lower initial void.

Last but not least, by observation, the volume change of the sample become less significant when the pre-consolidation pressure increases. It also can be understood as during the reconstitution process, the pressure needs to be controlled, in order to simulate the most "nature" soil. The purpose of doing reconstitution, is because all pervious stress history existed in a soil can be fully removed while the nature behaviour of a soil can still be remained therefore the test result can be considered as more accurate than the test conducted by using compacted soil. When a large pre-consolidation pressure is added, the soil is most likely become over dense, water can be squeezed out from soil quickly, as a result, the soil sample can have a unreal moisture content, void ratio and ect.

In stage 3, one SWCC test was carried out through use of a newly developed suction and temperature controlled oedometer and the temperature was maintained at 60°C. The main result finding of this test is that the water retention capacity decreases with increases of temperature at low suction stage. The influence becomes less significant at high suction.

4.2 Recommendations

The experimental work conducted during this study is limited within a small range of suction. Therefore, it is recommendation the future researchers can be carried out in the following areas:

Further SWCC test should be conducted with a larger suction range (> 1500 kPa). Therefore, the volume change behaviour of unsaturated soil under high suction could be better monitored and analysed.

As mentioned previously, SWCCs are affected by many factors such as the pore size distribution, pore shape distribution, specific surface area and particle size distribution. Therefore, those factors should be taken into account when conducting an experimental research.

Previous soil stress and suction history should also be monitored and taken into account when conducting an experimental research.

In current practice, two types of soil samples are often used in the laboratory: compacted and reconstituted soil sample. Research shows that most available experimental data are based on compacted soils. Because it is far easier to prepare a compacted soil sample rather than a reconstituted soil sample. However, it would be more appropriate to use reconstituted soil as the testing material. This is primarily because the stress history of the soil has been removed after reconstitution processes. Also, it will remove any previous exceeded factors which could influence the experimental result. Thus, reconstitution processes is a more precise method to simulate the soil under a natural state, yielding more reliable results.

The results of SWCC test under different temperatures are very limited. More experimental work should be carried out to investigate the effect of temperature on the behaviours of unsaturated soil. This aspect is usually neglected in current practices for simplification purpose.

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